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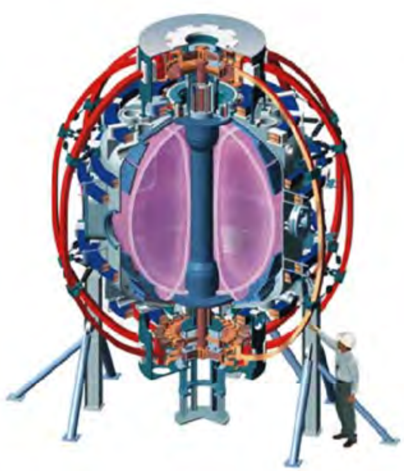
Coherent & Turbulent Fluctuation Measurements on NSTX Using Millimeter-Wave Reflectometry

S. Kubota, W.A. Peebles, N.A. Crocker, X.V. Nguyen
Institute of Plasma and Fusion Research, UCLA

G.J. Kramer, D.R. Mikkelsen, B.P. LeBlanc, R.E. Bell, S.M. Kaye, J.C. Hosea, J.R. Wilson, M. Ono, E.D. Fredrickson
Princeton Plasma Physics Laboratory

A. Ejiri
University of Tokyo



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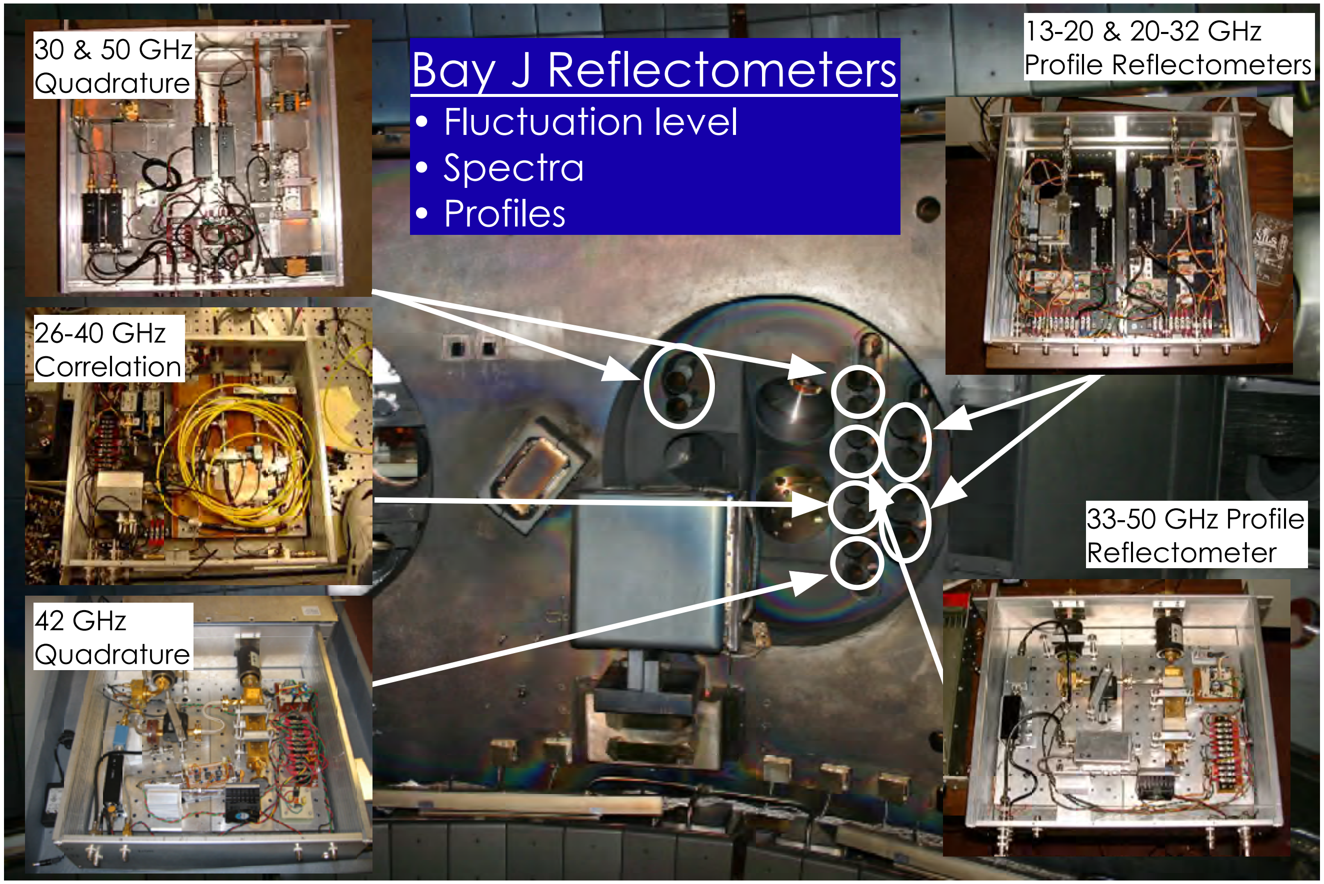
Abstract

Coherent & Turbulent Fluctuation Measurements on NSTX Using Millimeter-Wave Reflectometry[1]

Recently the millimeter-wave reflectometers on NSTX were modified to allow several new measurements of both coherent and turbulent density fluctuations in the core plasma. 1) The 28-40 GHz (0.97-2.0x10^{13} cm^{-3}, O-mode) correlation reflectometer has been upgraded from homodyne to quadrature detection, which allows the dual-channel system to measure fluctuation levels and poloidal flow in addition to radial correlation lengths. 2) A fixed frequency quadrature channel at 42 GHz (2.2x10^{13} cm^{-3}, O-mode) was been modified for detection of density oscillations associated with the HHFW launched at 30 MHz. Initial measurements show strong modulation of the reflected wave by both turbulent and coherent fluctuations. 3) Improvements to the FM-CW reflectometer (13-53 GHz, 0.2-3.5x10^{13} cm^{-3} for O-mode) now allow 10 ms repetition rates. Radial profile measurements of Δn for fast ion driven modes (EPM's and possibly low-frequency TAE's) are explored.

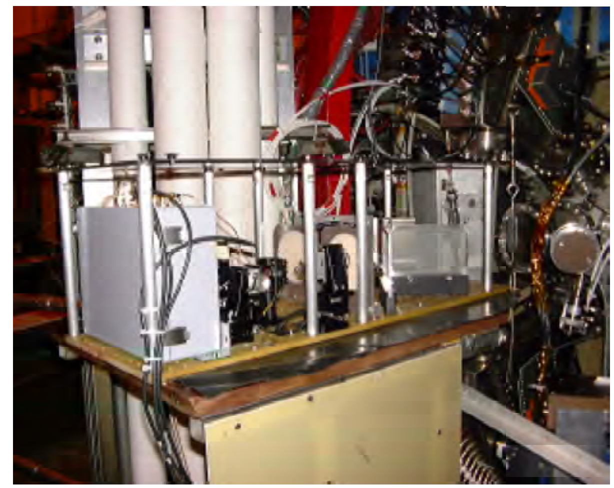
[1]Supported by U.S. DoE Grant DE-FG03-99ER54527.

Array of MM-Wave Diagnostics on NSTX



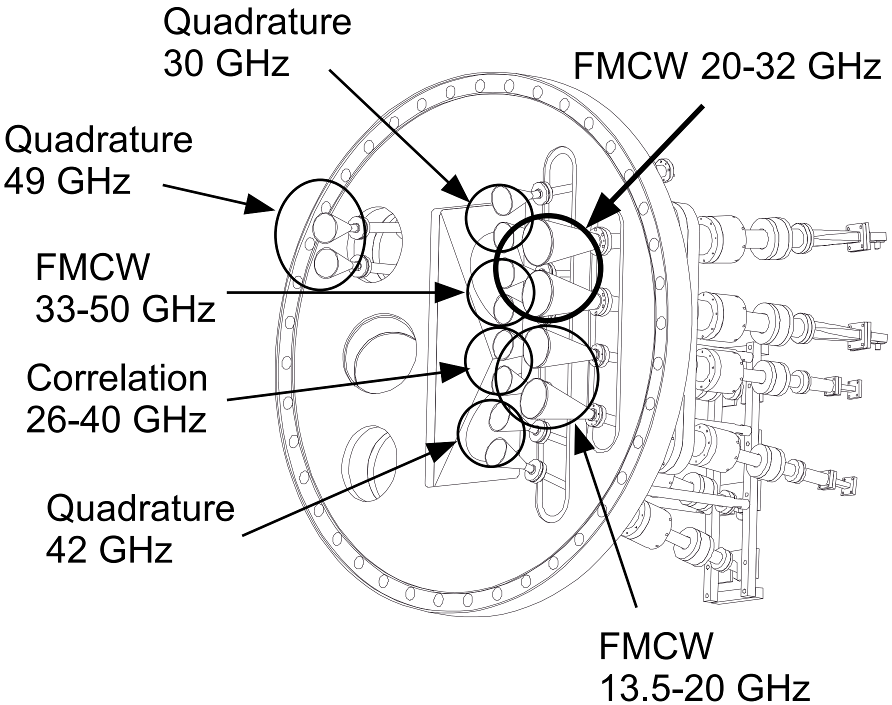
Bay G Interferometer

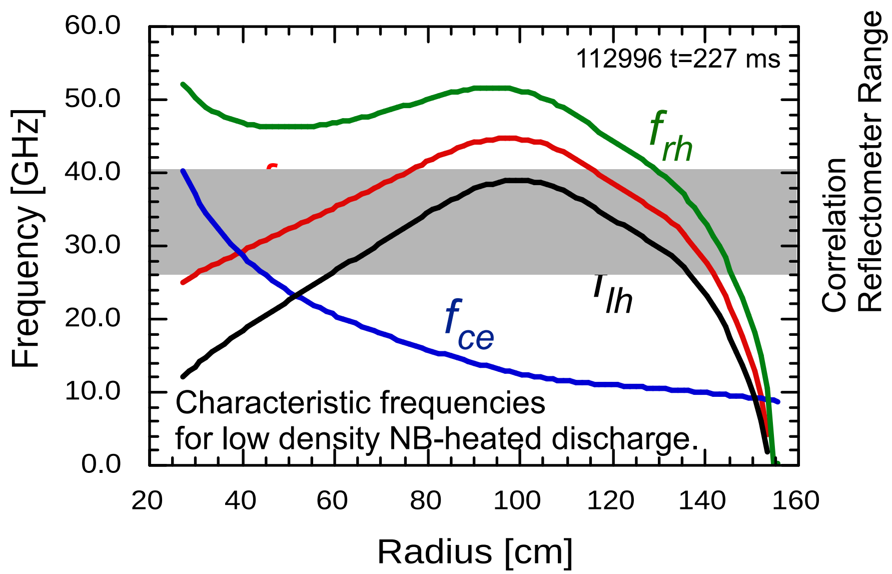
- Radial line density
- Operating routinely

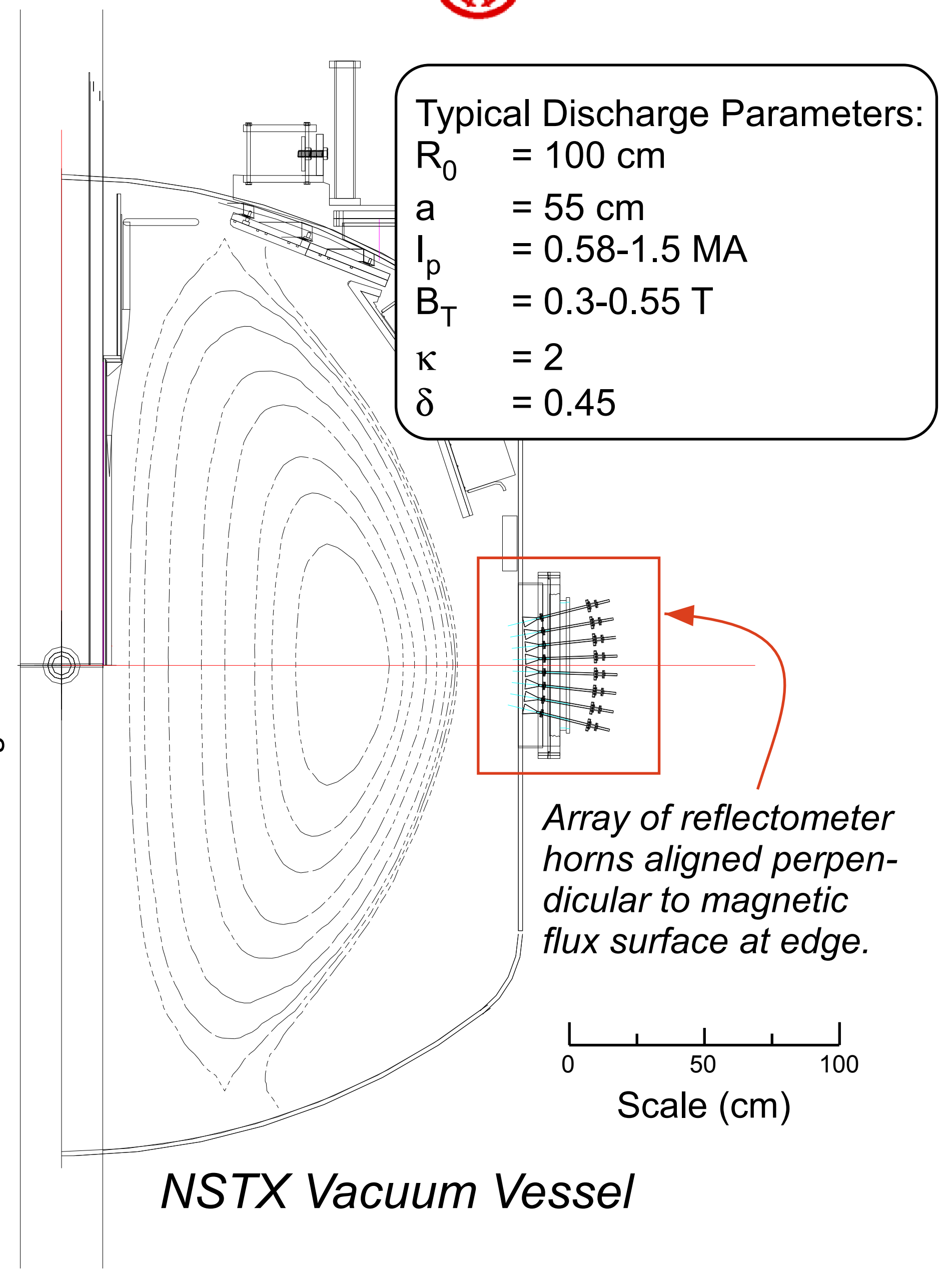


- **Array of microwave diagnostics for density measurements.**
- **Turbulence measurements in a variety of plasmas.**
- **Full-wave simulations for reflectometer response to modeled turbulence.**

Reflectometer Locations on NSTX







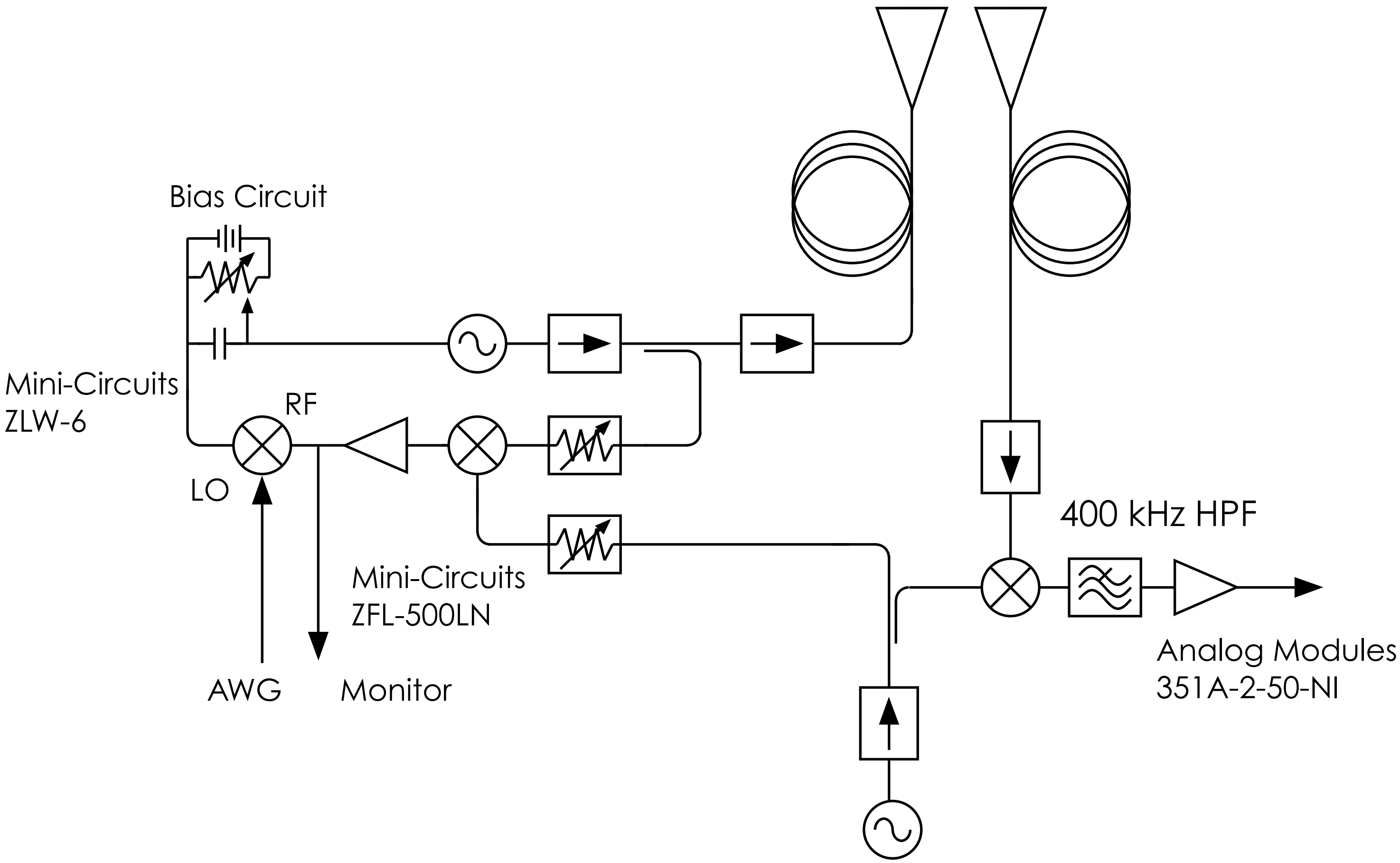
Introduction

- **Measurement of externally launched waves (30 MHz HHFW):**
  - Directionality of launch, magnitude of wave electric field ($\delta\varphi \propto E$).
  - Radial correlation for estimate of radial wavelength.
  - Contribute to understanding of HHFW propagation and interaction in core. Compliments edge ORNL reflectometer at HHFW antennas.
  - **For FY06, converted 42 GHz fixed-frequency homodyne quadrature channel to heterodyne reflectometer with Δf=27-32 MHz. ($f_{probe}<f_{lo}$). PoP measurements for core plasma.**
- **Radial density profile measurement of EPM's:**
  - Radial profile of plasma displacement can yield estimate of δB.
  - Magnitude, localization, radial structure, etc.
  - **Begun converting profile reflectometer for 10 μs repetition rate. Difficulty finding suitable IF amplifiers. Otherwise, OK for measurements down to $\delta n/n$~0.5%.**
- **Correlation reflectometry:**
  - Radial and poloidal correlations ($\delta n/n$, k spectrum, Lc, velocity).
  - All of this made possible by converting to quadrature detection.
  - **Preliminary measurements.**

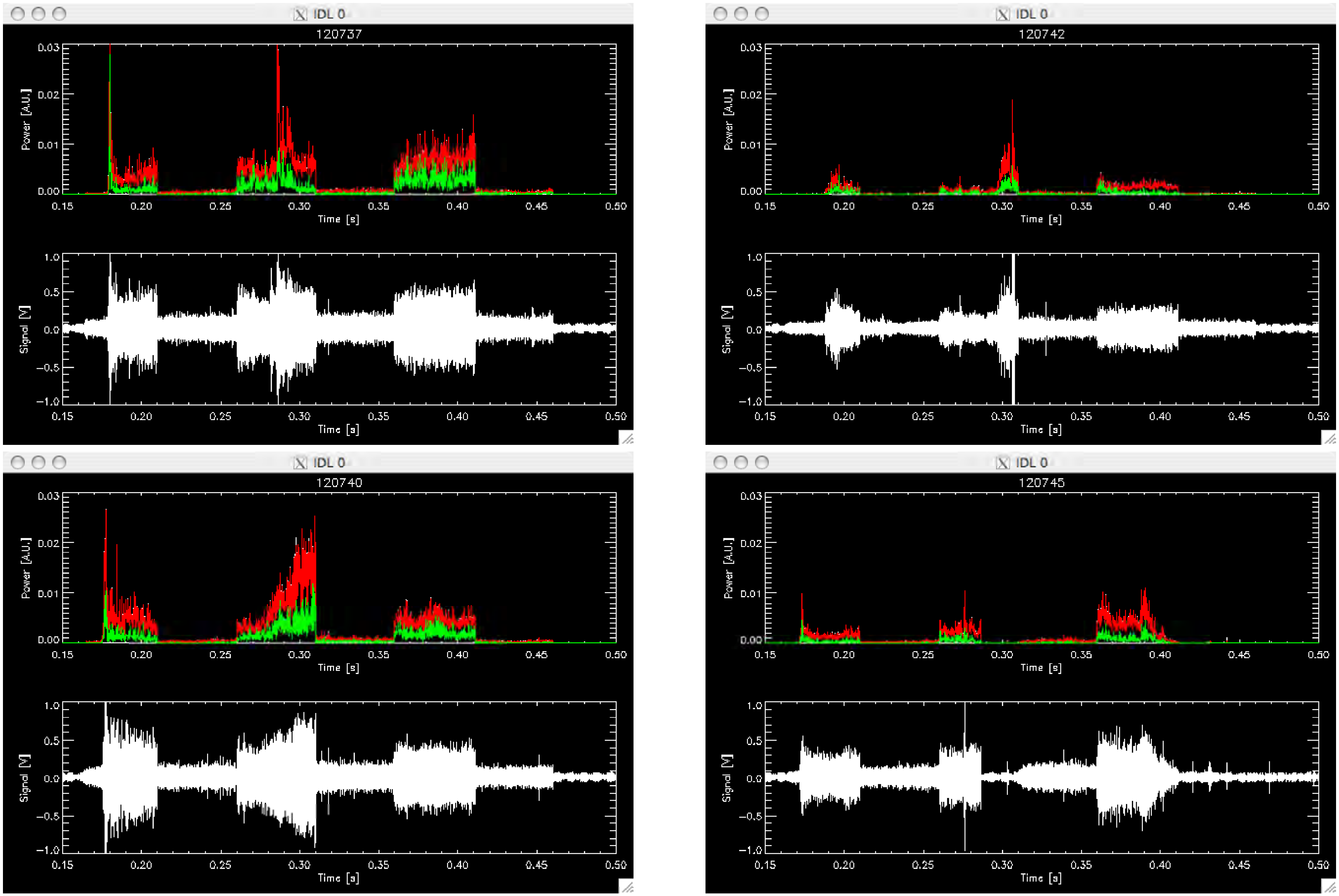
1. Reflectometer Modified for HHFW Measurements

NSTX

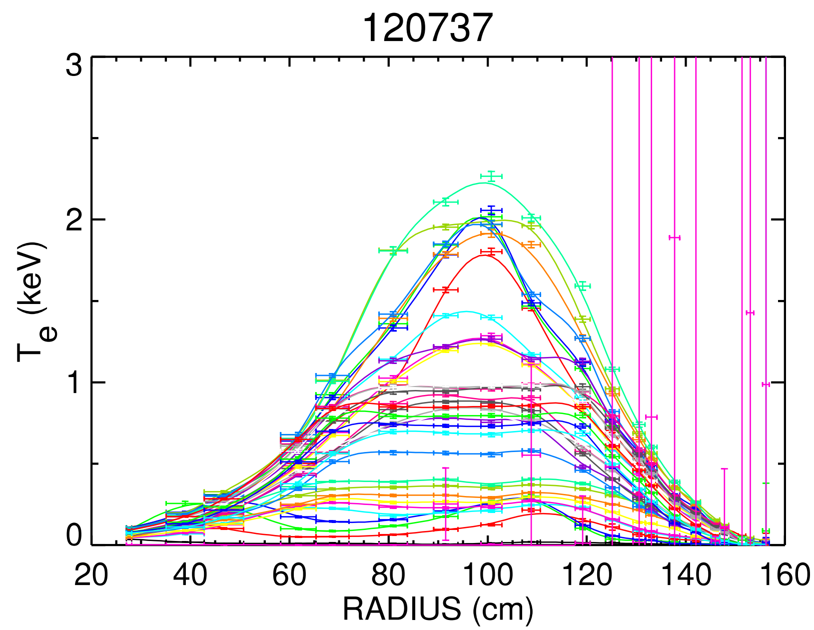
- **Heterodyne reflectometer with Δf=27-32 MHz around RF frequency of 30 MHz. $f_{probe} < f_{lo}$.**
  - Digitizer sampling rate of 8MSa/s.
  - LPF at 5 MHz, IF amplifier cutoff (6.5 MHz), digitizer cutoff 9 MHz.

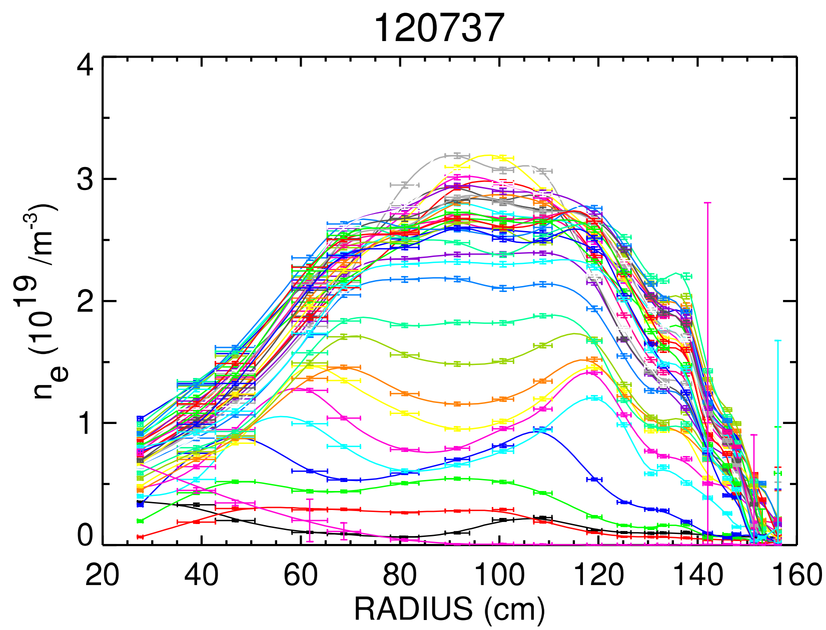


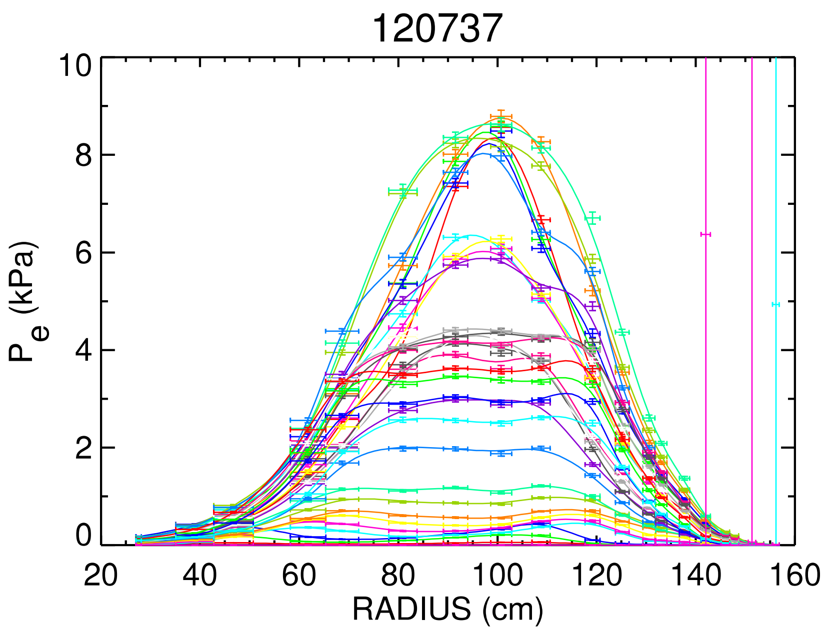
Signal and Power

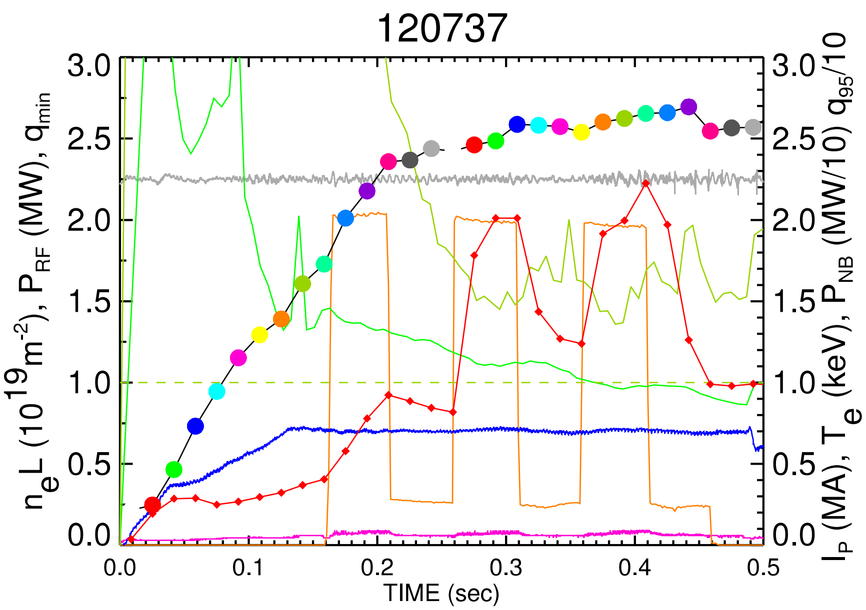


Initial Measurements During XP-617

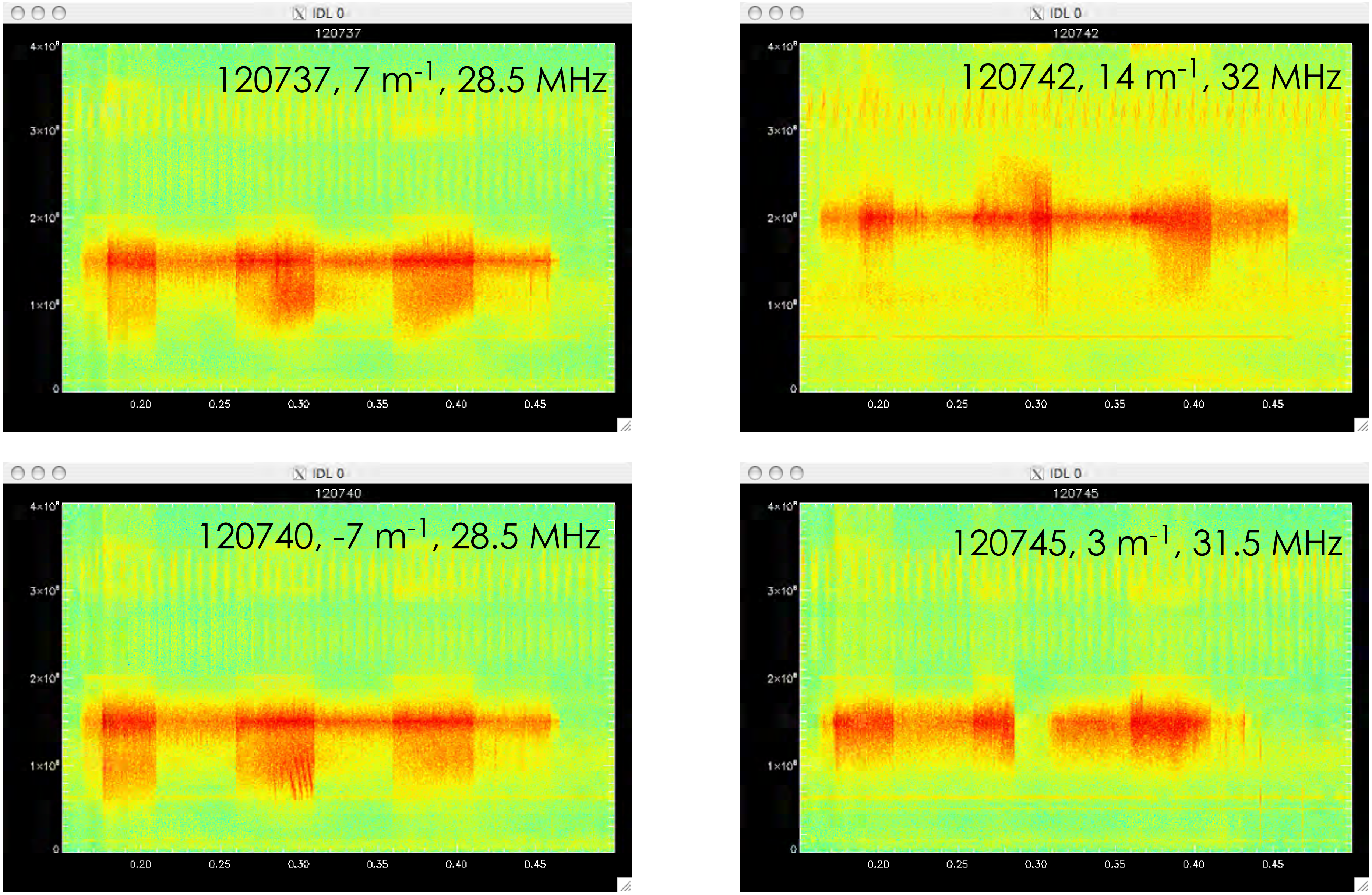








Signal Spectra, 5.5 kG



Noise/Pickup (A. Ejiri)

f_{IF}=28.5MH

3.5MHz:Aliased IF(28.5MHz)

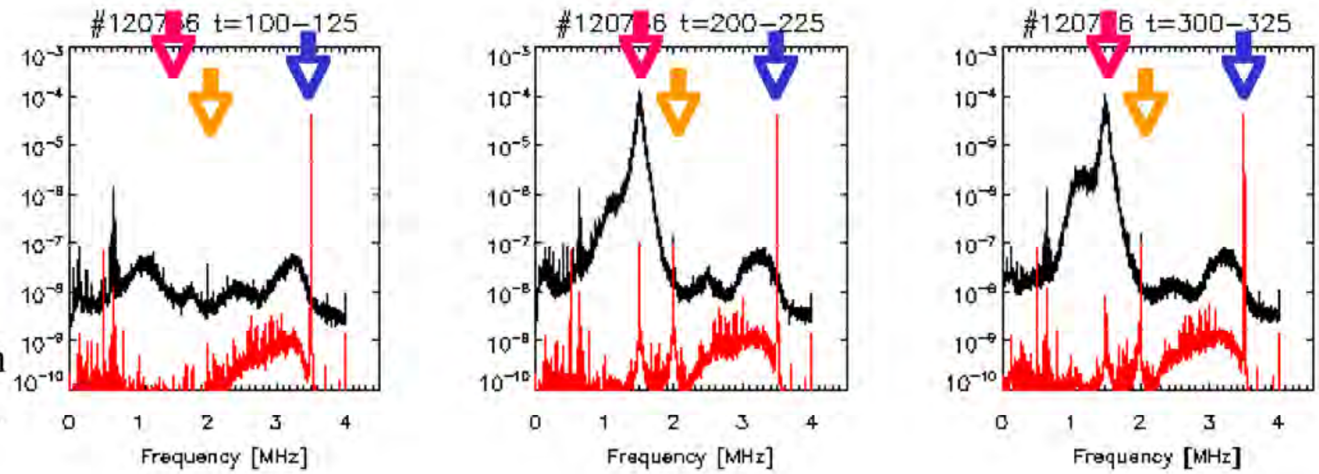
It is strong in 'mon', but also in 'signal'. Very narrow spectrum.

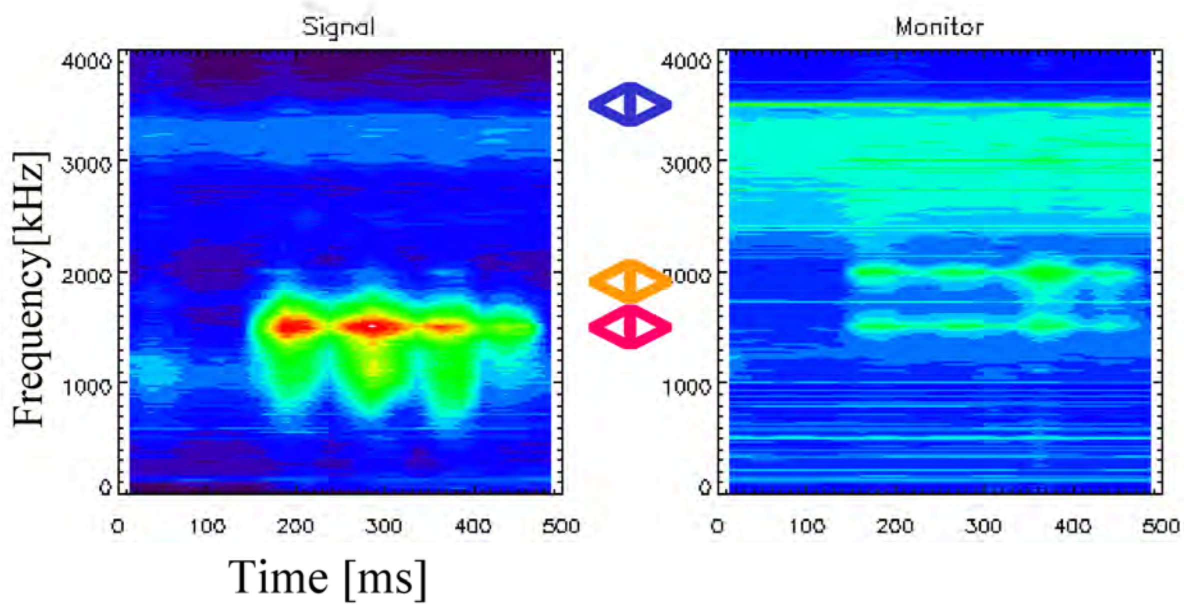
2MHz:Aliased 30MHz

Direct RF pickup. Narrow, but some broadening

1.5MHz:Target RF

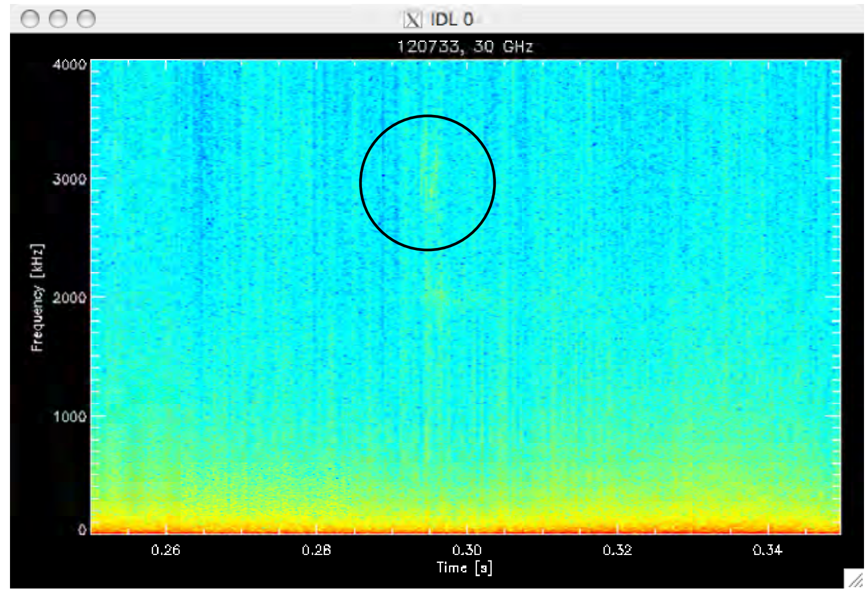
It also appears in 'mon', which means source modulation or contamination of 'signal' into 'mon' via unexpected microwave path.

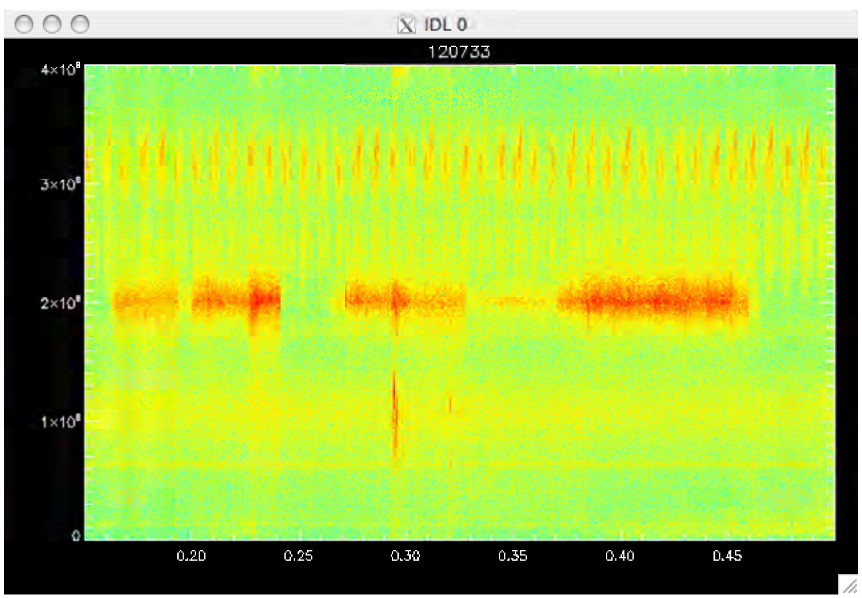


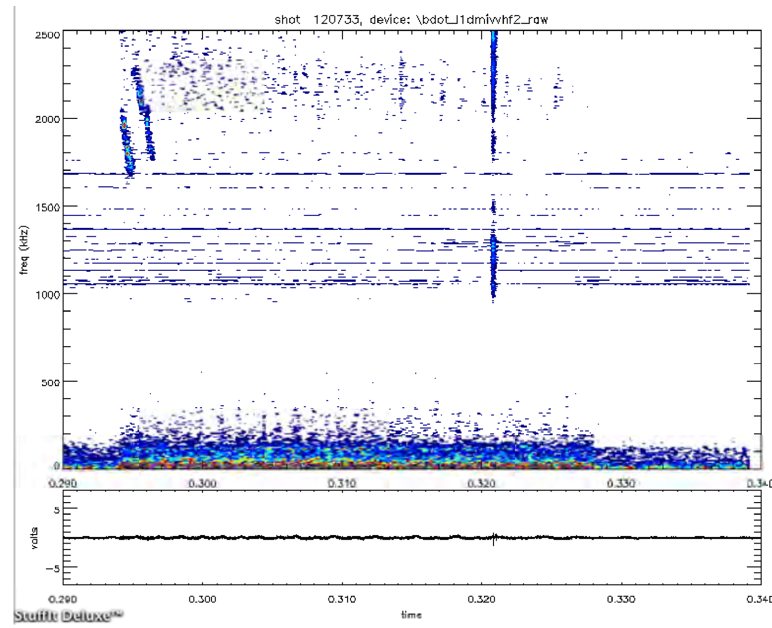


Summary and Future Work

- **Signal characteristics:**
  - Broad turbulence spectrum.
  - Typically asymmetric.
  - Broad offset sidebands.
  - Coherent chirps.
- **Future work:**
  - Modifications to estimate $\delta\varphi$.
  - Multiple channels?
  - Further noise checks.
  - Scattering of HHFW by fluctuations.



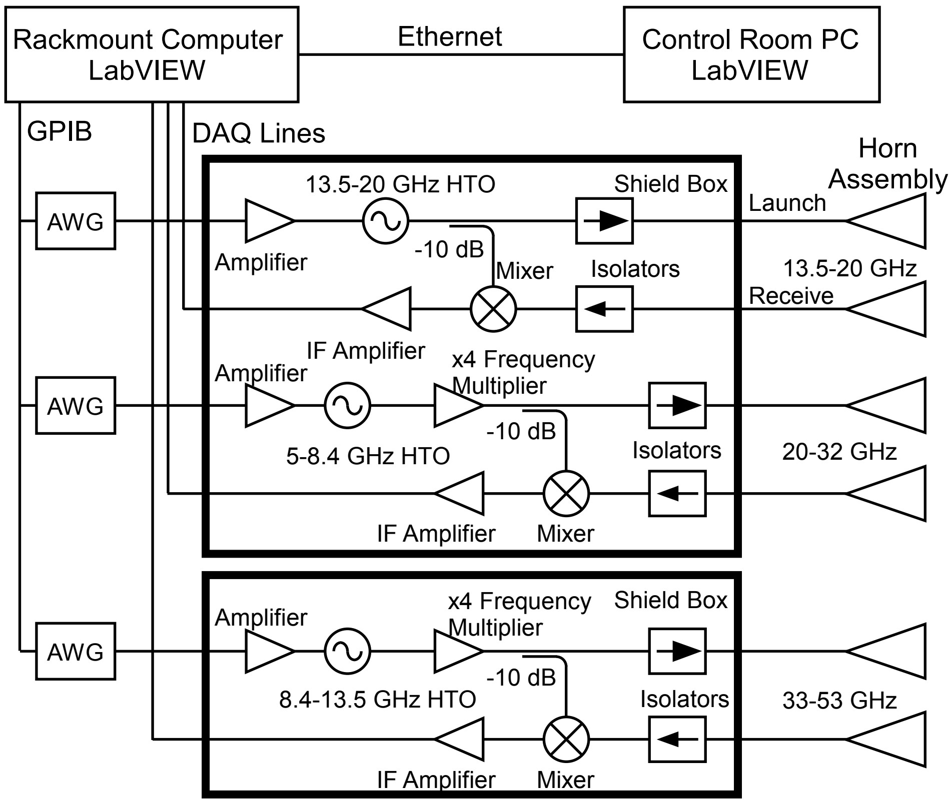


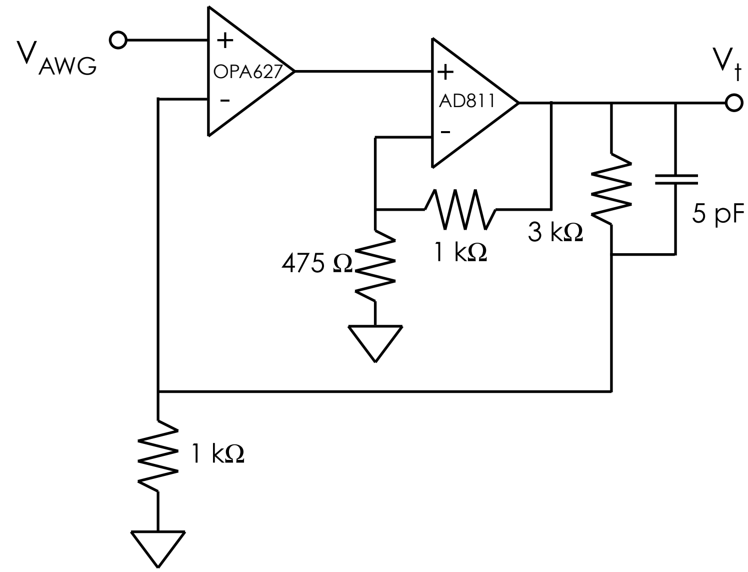


2. Fast Profile Reflectometry: Background

- Unique magnetic geometry of the spherical torus makes NSTX susceptible to an abundance of fast ion driven instabilities ranging in frequency around ten kHz to several MHz.
- While compressional Alfven eigenmodes (CAE's) exist in the MHz range of frequencies, energetic particle modes (EPM's) and toroidal Alfven eigenmodes(TAE's) are typically found below ~200 kHz.
- Usually mode structure and amplitude can only be inferred from external magnetic measurements.
- Homodyne quadrature reflectometers provide three point measurement at 30, 42, and 49.8 GHz.
- Motivation for the upgrades to the FM-CW system is the direct measurement (over a large fraction of the outboard minor radius) of the internal spatial structure and amplitude of these as well as other low frequency MHD instabilities (e.g. internal kinks, neoclassical tearing modes, resistive wall modes).
- This information is crucial for better understanding these instabilities as well as for modeling their interactions and effects on fast-particle confinement, which is an important topic for ITER.

FM-CW Reflecometer Circuitry





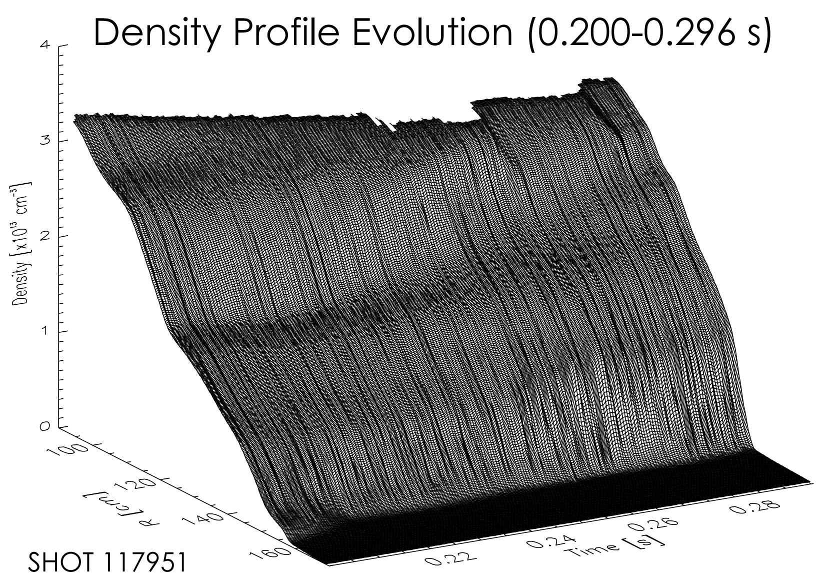
FMCW System

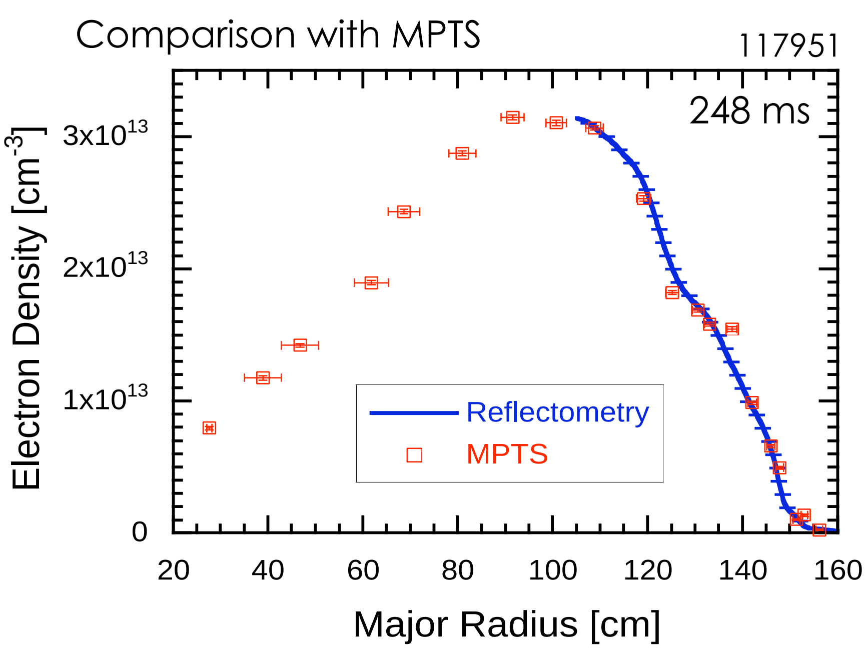
- 13-53 GHz coverage (2.1×10^{12} to 3.5×10^{13} cm^{-3}).
- Maximum repetition rate of 20 μs/sweep (3840 total profiles per shot).
- Using spline fit to Thomson edge profile below $n_e = 9 \times 10^{11}$ cm^{-3}.

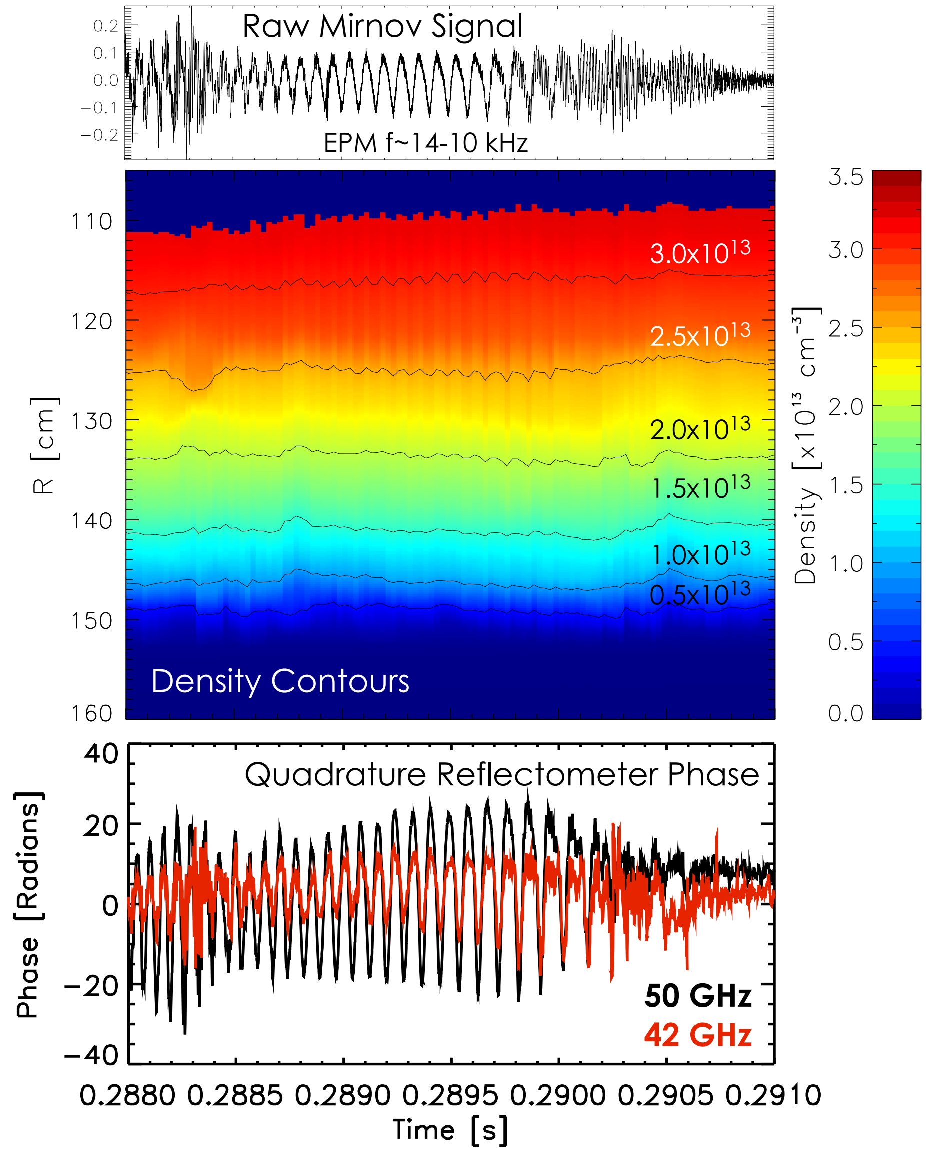
Modifications for 10 µs Repetition Interval

- IF amplifier bandwidth (0.05-130 MHz).
- Data acquisition at 100 MSa/s.
- Agilent 33220A: 14-bit, 50 MSa/s, 64 kSa.
- Tuning voltage x4 amplifier bandwidth increased to 10 MHz.

Measurements at 25 μs Repetition Rate

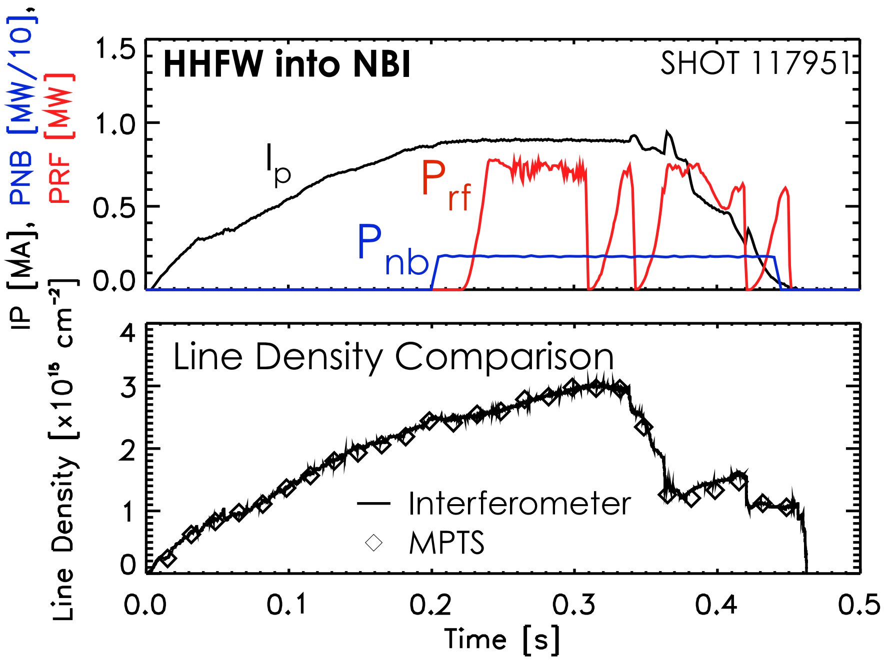


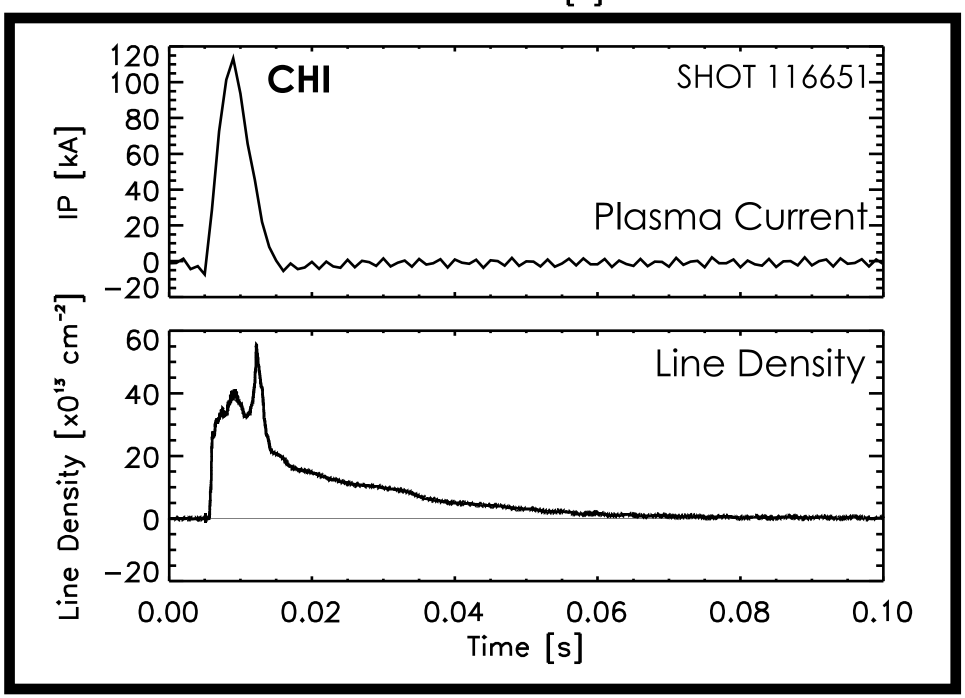


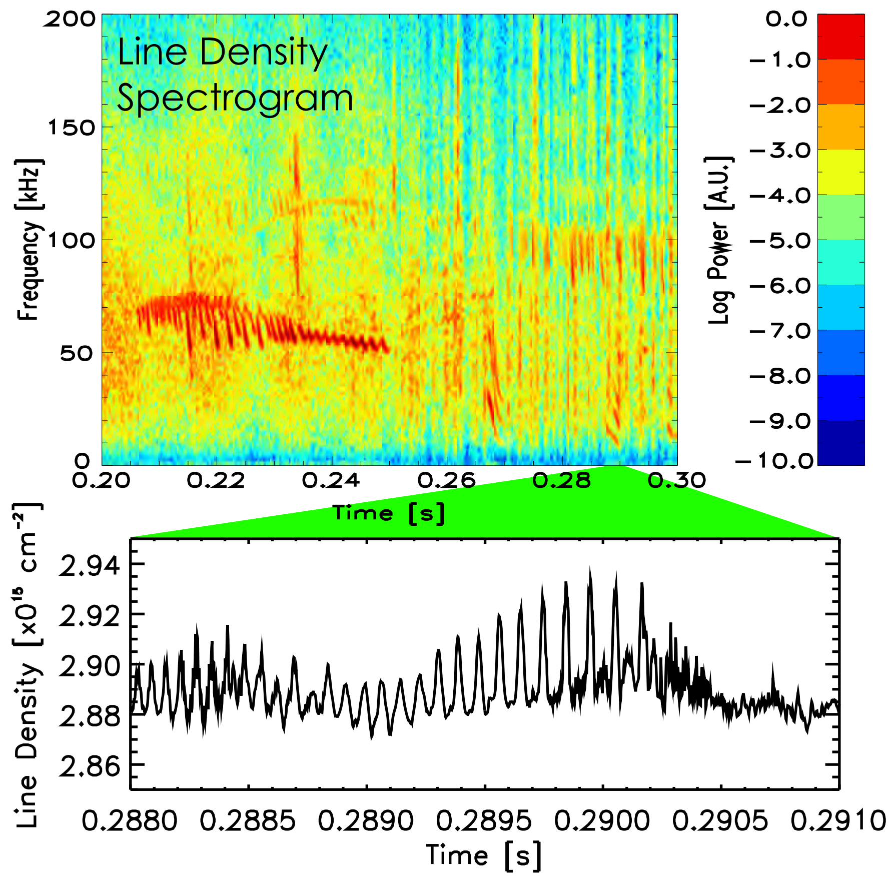


- **Radial mode structure is visible.**

1mm Interferometer Provides Time-Resolved Line Density







- Valuable for studying coherent modes and turbulence.
- Can provide constraint on fluctuation levels at midplane.
- Data partially available on tree. Need to start looking at this.

Summary and Future Work

- 10 μs repetition interval now possible on NSTX. Some initial measurements made.
- Some key issues for measurements of fluctuation level radial profile identified.
  - Tuning voltage amplifier bandwidth.
  - AWG characteristics.
- Future work:
  - Can we lower nonlinearities in frequency sweep even further? Possibly will need to combine hardware and software techniques.
  - Faster sweeps.

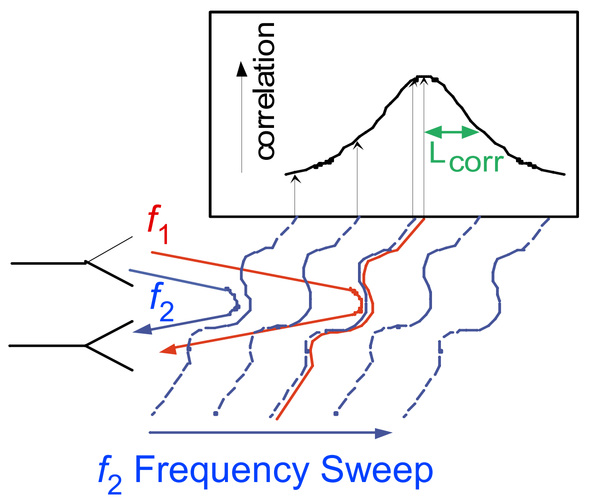
3. Correlation Reflectometry: Background

- Core transport of long wavelength turbulence (ITG modes, TEM's, micro-tearing modes with $k_\theta \rho_s \leq 1$) thought to be suppressed due to increased ExB shear, T_i/T_e ratio and gradient β effects.
- Reflectometry on NSTX has focused on measuring density fluctuation levels and radial correlation lengths in low density L-mode discharges.
- Reflectometer correlation lengths (L_r) are calculated from 1/e decorrelation distance of homodyne signals and show similar values over a wide variety of discharges (NB- and RF-heated, He Ohmic). Typical results:
  - L_r increases from ~2 cm near edge to ~10-20 cm in core. These values are ~5-20 x ρ_s. Correlation lengths always increase towards the core.
- **Studies using full-wave simulations have shown that density turbulence correlation lengths (L_n) can be different from L_r.**
  - **Strongly dependent on δn/n, *k*-spectrum.**
- **Focus of present study:**
  - **Quadrature correlation reflectometry for estimates of unknown parameters.**
  - **Simulated turbulence with full-wave simulations to estimate values such as L_n and δn/n.**

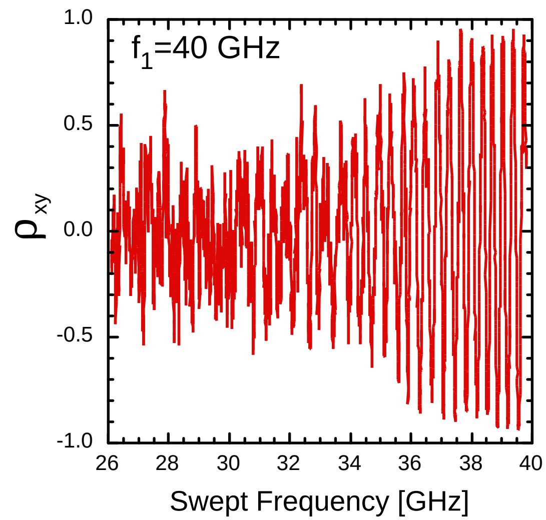
Homodyne Radial Correlation Reflectometry

NSTX

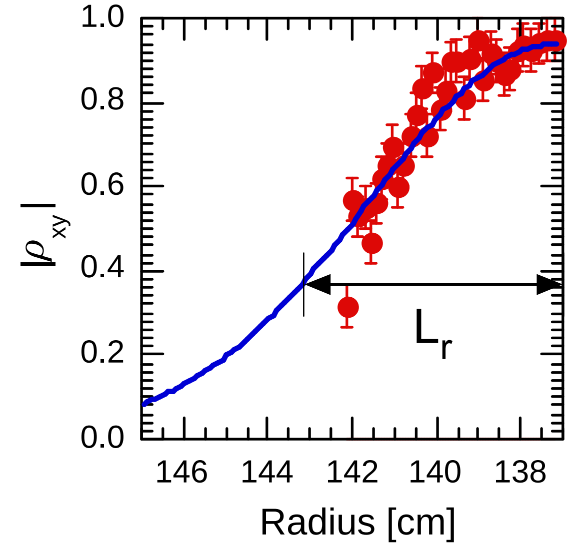
Principle of Radial Correlation Length Measurements



Correlation Coefficient Function vs Swept Frequency



Correlation Coefficient Function Envelope vs Radius



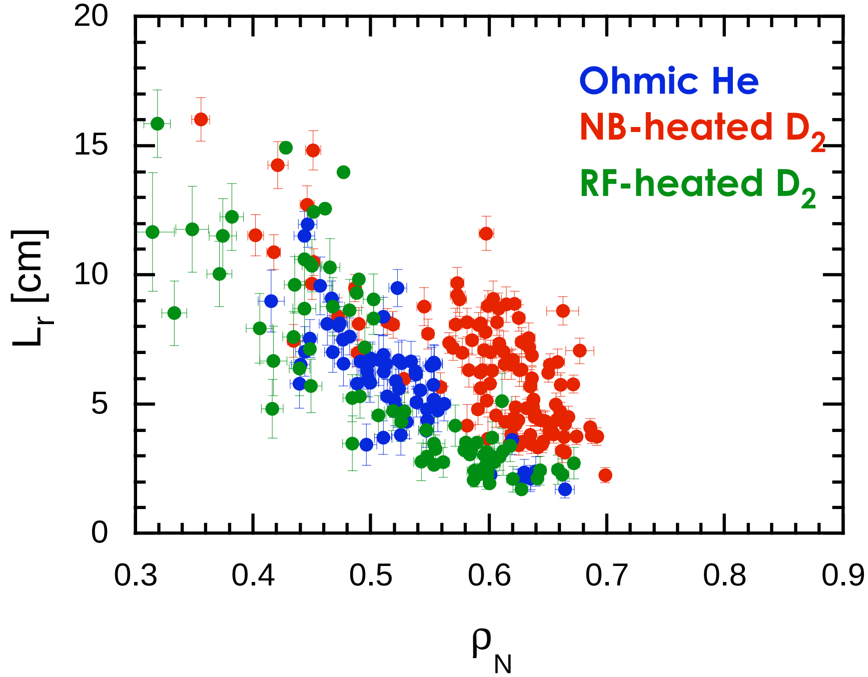
- Fixed frequency f_1 and swept frequency f_2 with identical launch and receive horns reflect from different cutoff layers in the plasma.
- **Correlation coefficient function** of homodyne signals x and y is modulated by the swept DC phase of f_2.

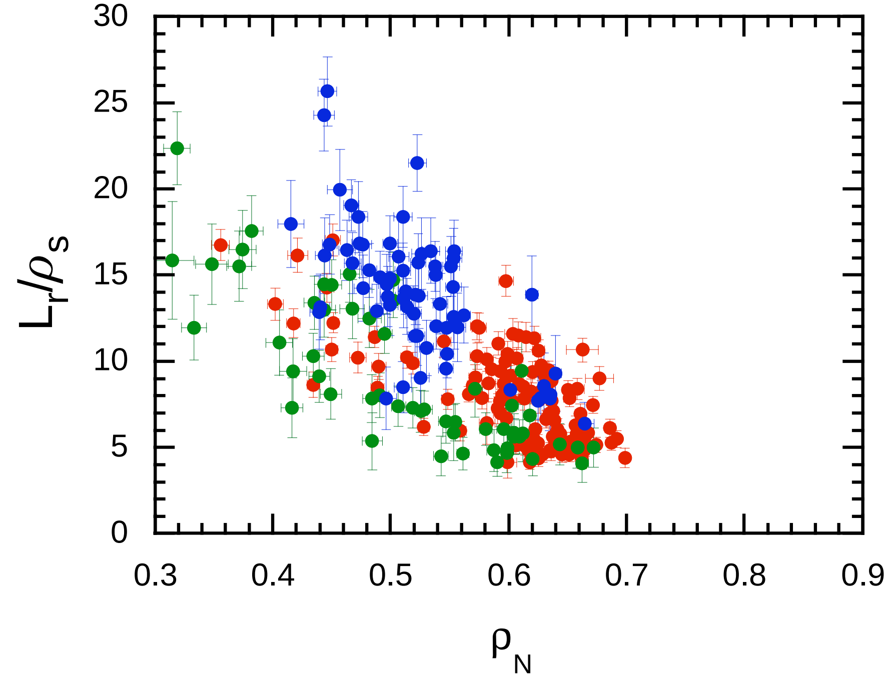
$$\rho_{xy} = \frac{\langle (x-\langle x\rangle)(y-\langle y\rangle)\rangle}{\sqrt{\langle (x-\langle x\rangle)^2\rangle}\sqrt{\langle (y-\langle y\rangle)^2\rangle}}$$

- Envelope of correlation coefficient function mapped from from frequency to radial position using density profiles from Thomson scatteing.
- Correlation length L_r is defined here as the e-folding distance of the correlation coefficient function envelope (best fit to Gaussian).

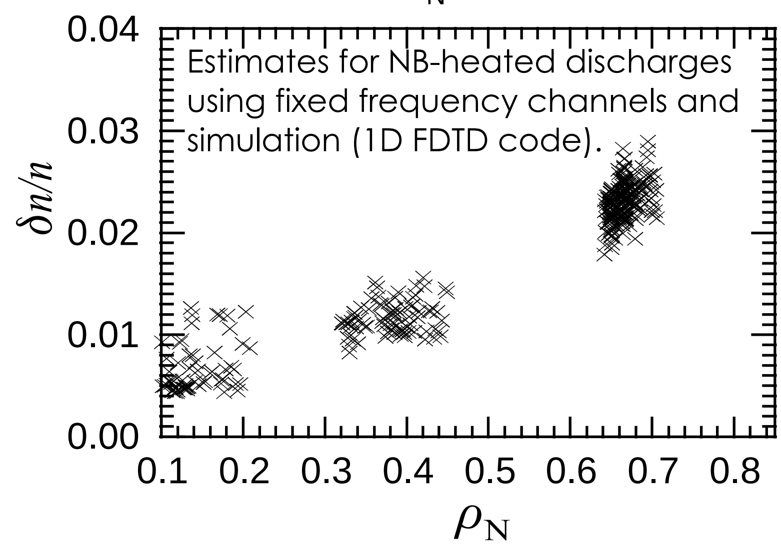
L_r Compared in a Variety of L-Mode Plasmas

Ohmic(He)/NB-heated(D_2)/RF(D_2)





- Ohmic (He), RF- & NB-heated L-modes.
  - L_r~2-15 cm from r~0.7-0.3 are seen irrespective of heating method.
- Dependencies:
  - Seems to scale with ρ_s at given radius.
  - L_r and L_r/ρ_s decrease with radius.
- **Really want turbulence correlation length L_n instead of L_r to look at scaling, etc.**

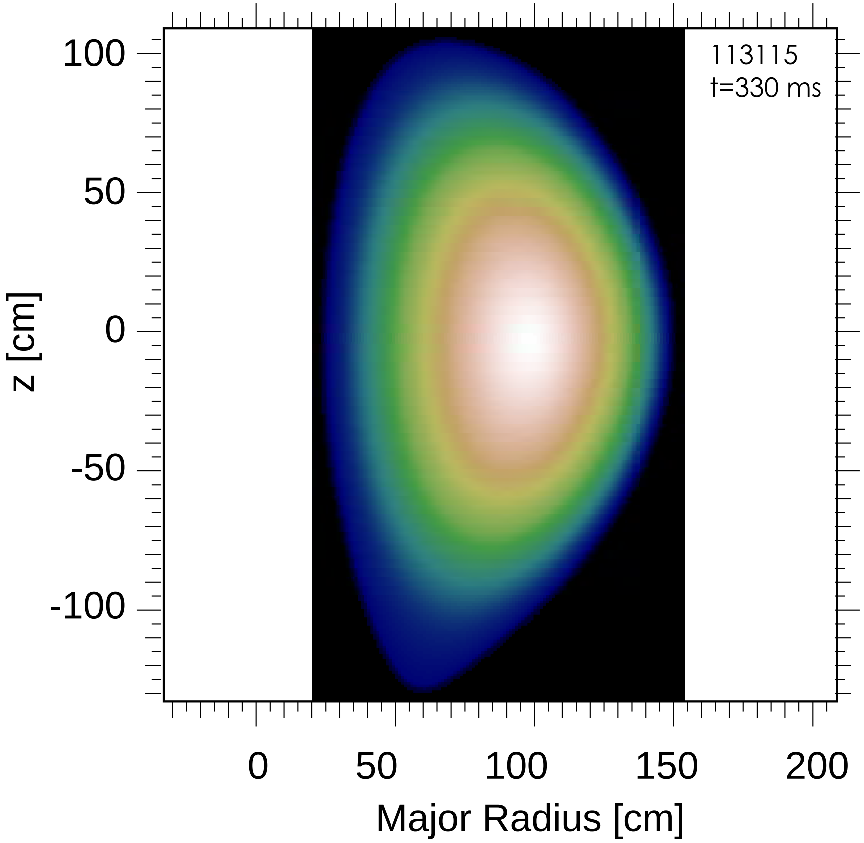


Role of Simulations with Modeled Turbulence and Full-Wave Code

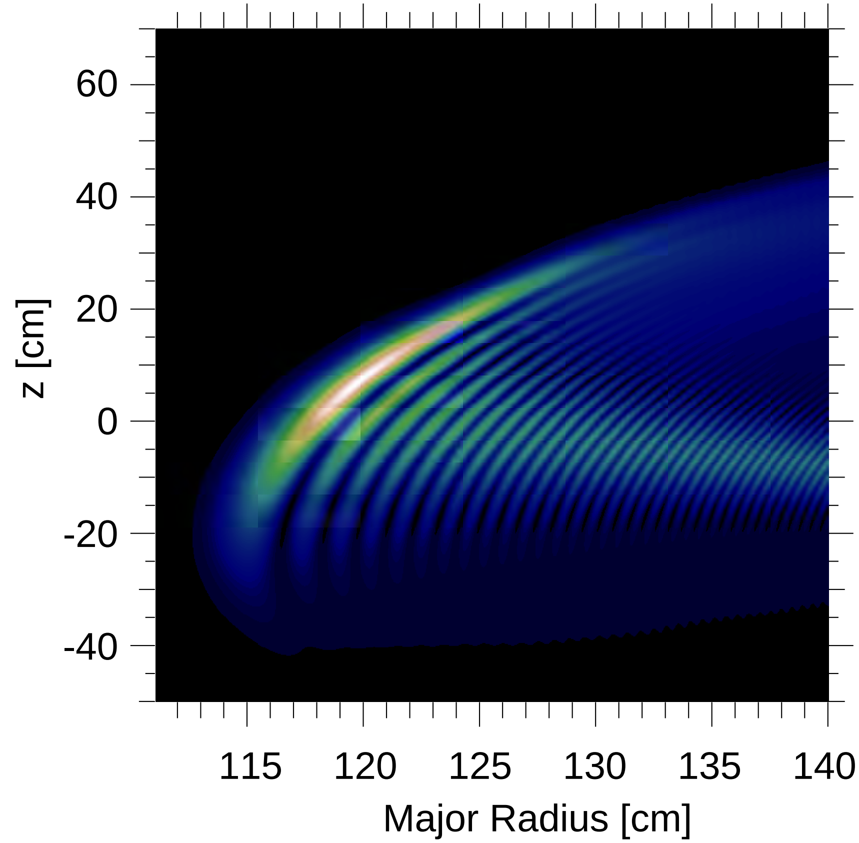
- **Experiment**
  - Real turbulence in 3-D space evolving in time.
  - Reflectometer response from turbulence is time-dependent complex signal dependent not only on turbulence properties but also on stationary background profiles as well as antenna geometry, etc.
  - Statistical properties of reflectometers signal usually equated to statistical properties of turbulence (spectra, level, correlations, etc.). This is in general not correct.
- **Simulation of Turbulence**
  - Use simple model for density fluctuations with certain statistical quantities as input (k and ω spectra, $\delta n/n$, correlation length and time).
- **Full-Wave Code for Reflectometer Response**
  - Background profiles (density, temperature, flow, etc.) are estimated from other diagnostics.
  - Accurate geometry of plasma with respect to reflectometer horns.
- **Comparison Between Experiment and Simulation**
  - Use statistical optics.

PPPL 2-D Full-Wave Code (FWR2D)

Density Contours



Wave Amplitude for 42 GHz O-Mode



- 2-D density and temperature contours from MPTS or reflectometer and EFIT.
- Propagation of electric field amplitude E(x,t) described by

$$2i\omega\frac{\partial E}{\partial t} + \mathcal{L}E = 0, \qquad \mathcal{L} = c^2\nabla^2 + \omega^2\varepsilon$$

- ε is O- or X-mode dielectric.
- E.J. Valeo, G.J. Kramer, R. Nazikian, Plasma Phys. Control. Fusion 44, L1 (2002).

Turbulence Model and Statistical Optics

- **Turbulence Model:** Sinusoids with random phase and obeying:

$$\frac{1}{n^2}\langle \tilde{n}_1 \tilde{n}_2 \rangle = \left(\frac{\tilde{n}}{n}\right)^2 \exp\left(-\left(\frac{\Delta t}{\tau}\right)^2\right) \exp\left(-\left(\frac{(\Delta \mathbf{r} + \mathbf{v}\Delta t)\cdot \Delta \mathbf{k}}{2}\right)^2\right) \cos\left(\mathbf{k}_m \cdot \Delta \mathbf{r}\right)$$

$\tilde{n}/n$: density fluctuation level $\qquad \Delta \mathbf{r} = \mathbf{r}_2 - \mathbf{r}_1$

τ: correlation time $\qquad \Delta t = t_2 - t_1$

$\Delta \mathbf{k}$: wavenumber spread

$\mathbf{k}_m$: wavenumber mean

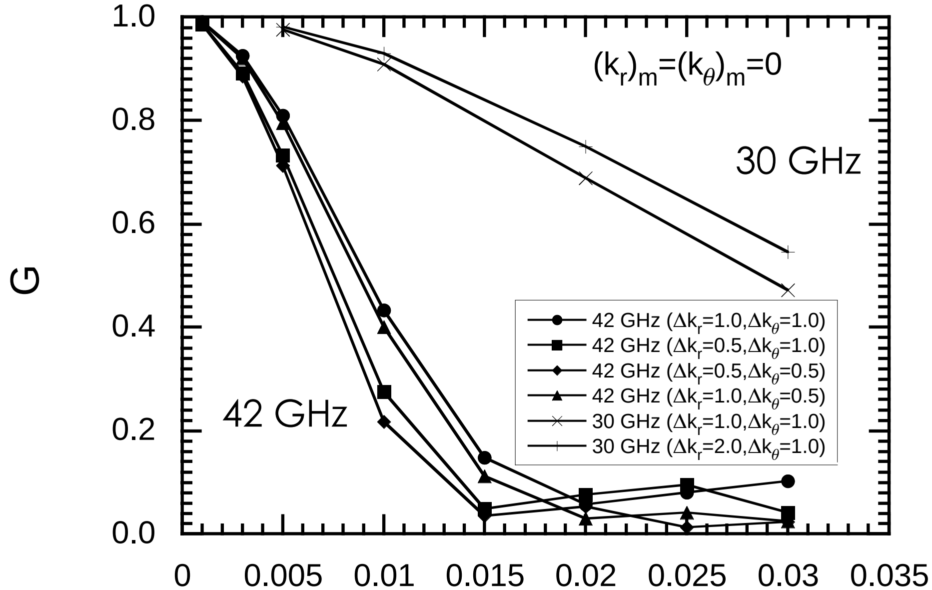
- **Statistical Optics:**
  - Coherent reflection (strong function of $\delta n/n$):

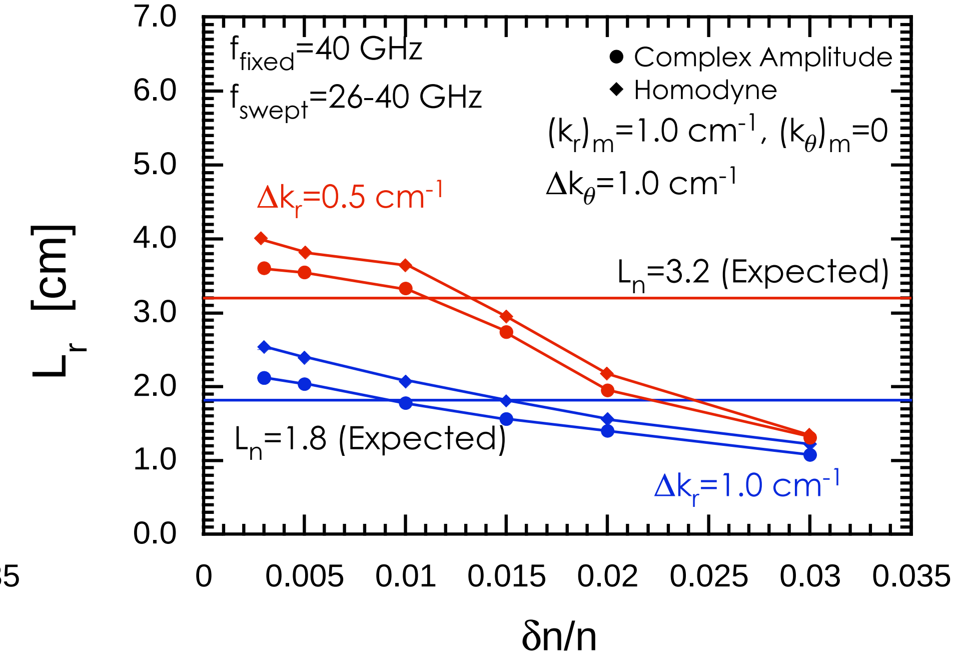
$$G = \frac{|\langle E \rangle|}{\sqrt{\langle |E|^2 \rangle}}$$

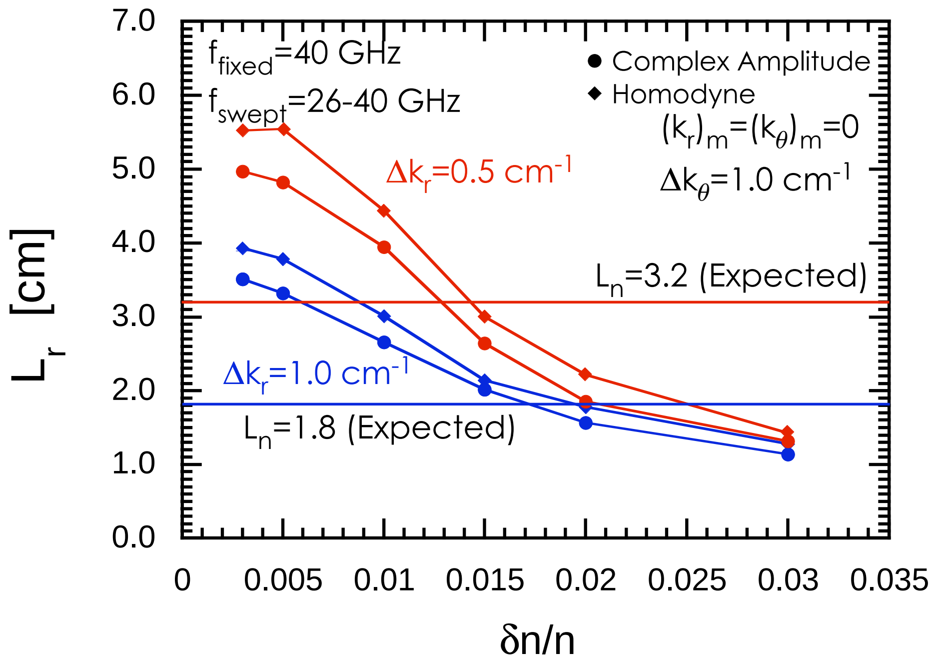
  - Normalized cross-correlation or L_r (strong function of L_n and $\delta n/n$):

$$\gamma = \frac{|\langle E_1 E_2^* \rangle|}{\sqrt{\langle |E_1|^2 \rangle \langle |E_2|^2 \rangle}}$$

Turbulence Estimates from Reflectometry Simulations







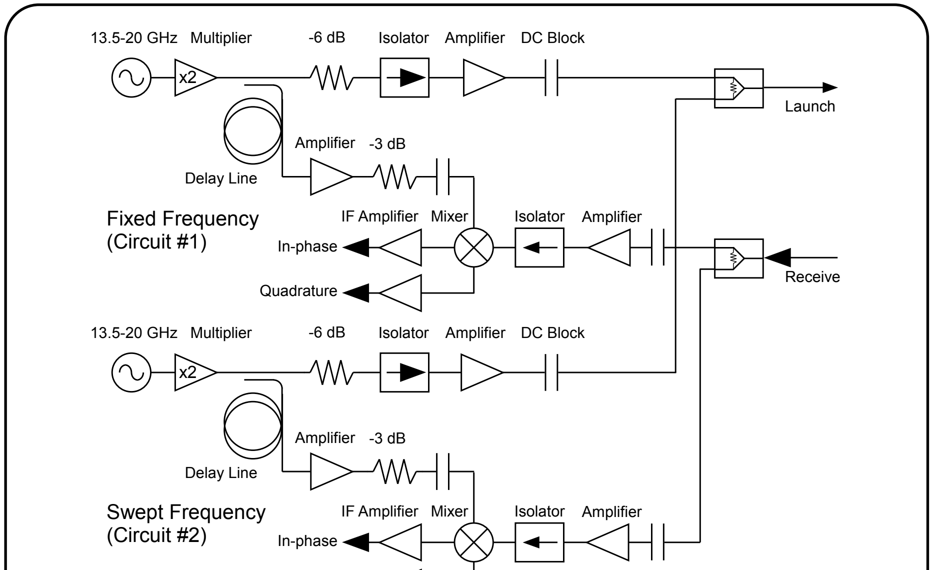
- Shot 113115, t=330 ms.
- Comparison of correlation and quadrature reflectometry data with simulations.
- Experimental results: L_r=~11.4 cm
  G~0.85 for 42 GHz, ~0.6 for 30 GHz.
- Homodyne tracks complex amplitude L_r well but overestimates slightly.
- **L_r is strongly dependent on $\delta n/n$ and k_r spectral shape.**
- **Relatively independent of k_θ.**

What Do Simulations Tell Us About Homodyne Reflectometry?

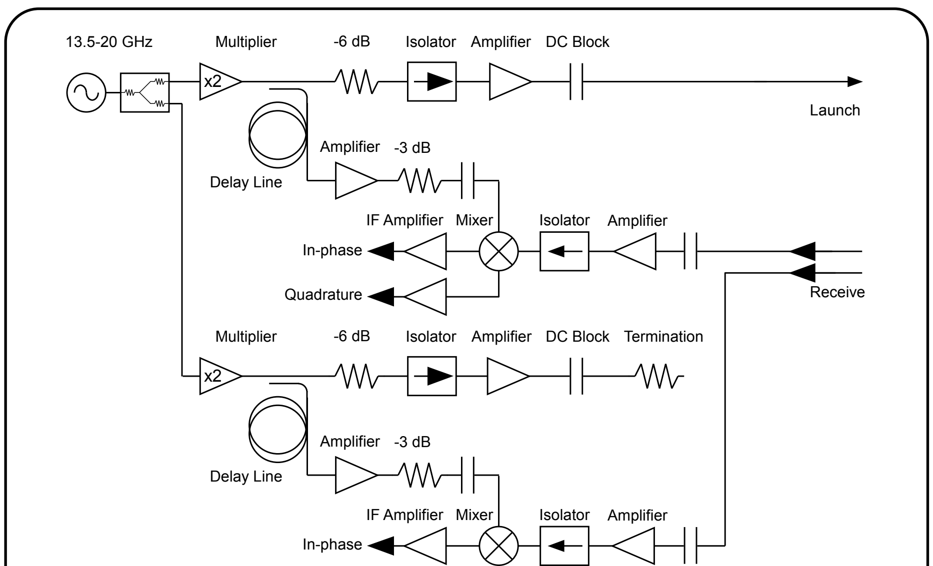
NSTX

- According to 2-D full-wave code:
  - Phase response not a good measure of turbulence quantities.
  - Homodyne signal and complex signals offer similar L_r. Satisfactory if turbulence is not evolving.
  - L_r can vary significantly from actual turbulence density correlation length. Strongly dependent on $\delta n/n$ and k_r. Less dependent on other parameters.
- $\delta n/n$ dependence may explain consistent observation of large correlation lengths (10-20 cm) observed in core.
- **Corroboration of code/turbulence model with experiments is still limited. Definitive test to be performed on DIII-D including detailed comparison with BES.**
- Future work:
  - Continue 2-D reflectometry simulations for different plasma conditions. In particular, consider radial variation of turbulence wavenumber spectra and $\delta n/n$.
  - Include flows. Consider correlation time, spectra.
  - Comparison with global non-linear gyrokinetic simulations (GYRO).
- **Need more turbulence information to accurately model.**

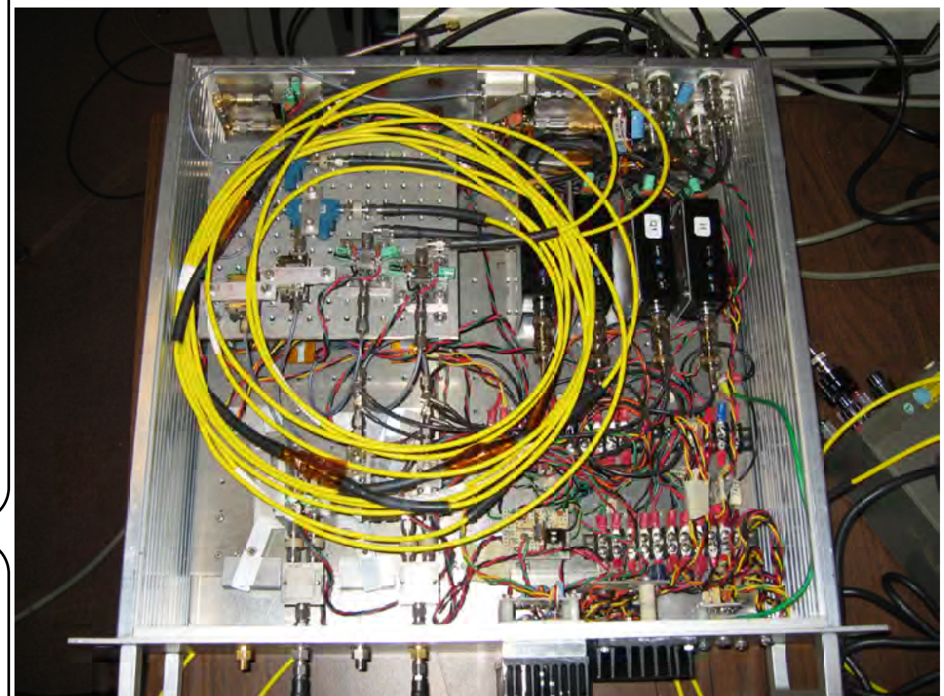
New Quadrature Correlation Reflectometer



Radial Correlation



Poloidal Correlation

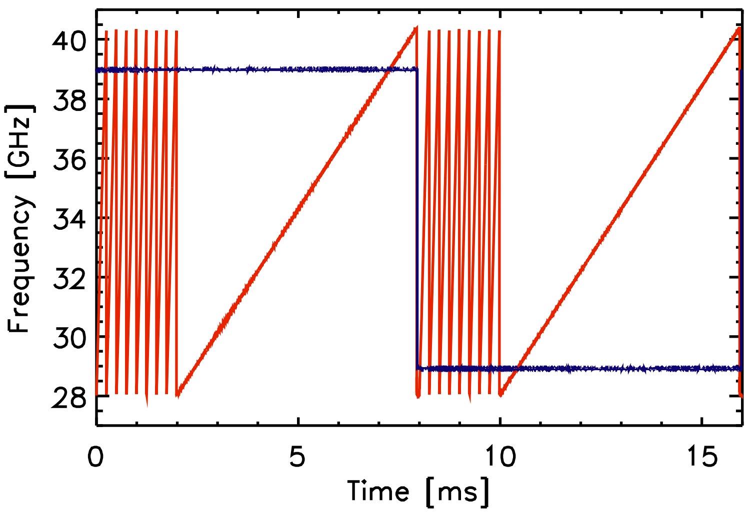


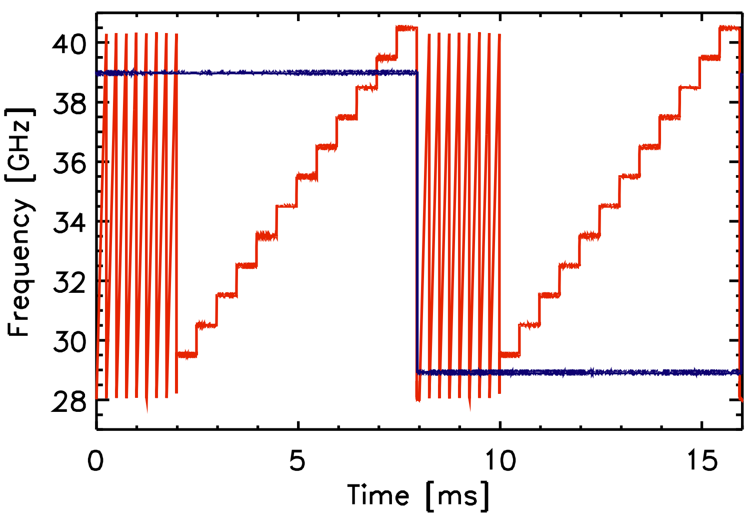
- Reflectometer uses direct-conversion quadrature detection.
- Complex signal (amplitude and phase information).
- Configured for either radial or poloidal correlation measurements.

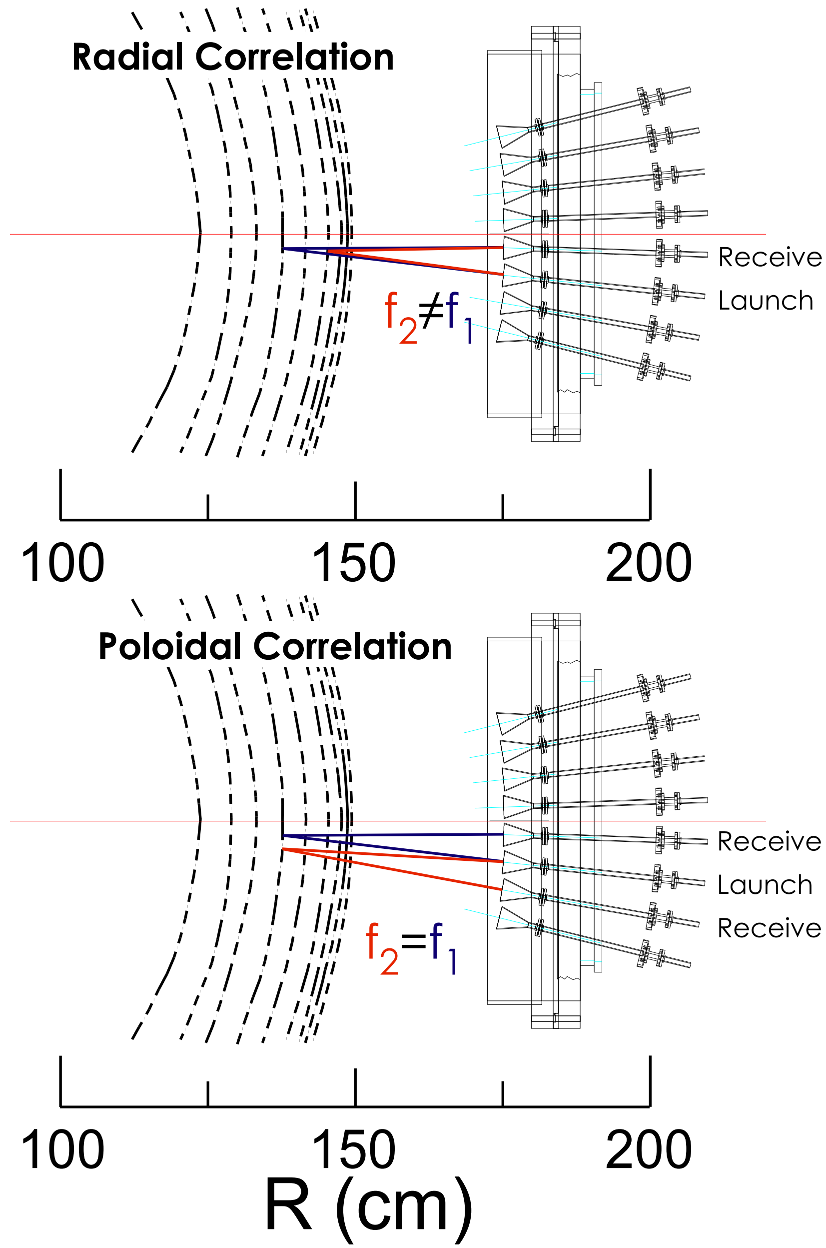
Poloidal and Radial Correlation Measurements

NSTX

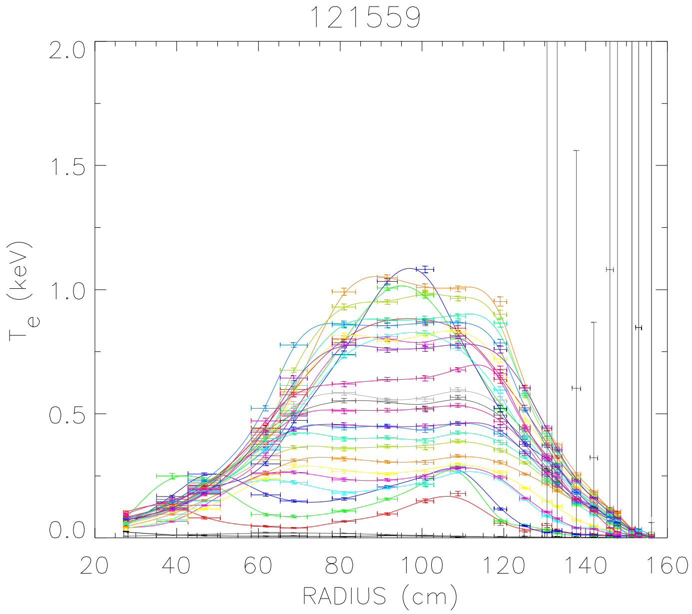
Sample of Frequency Sweep Waveforms

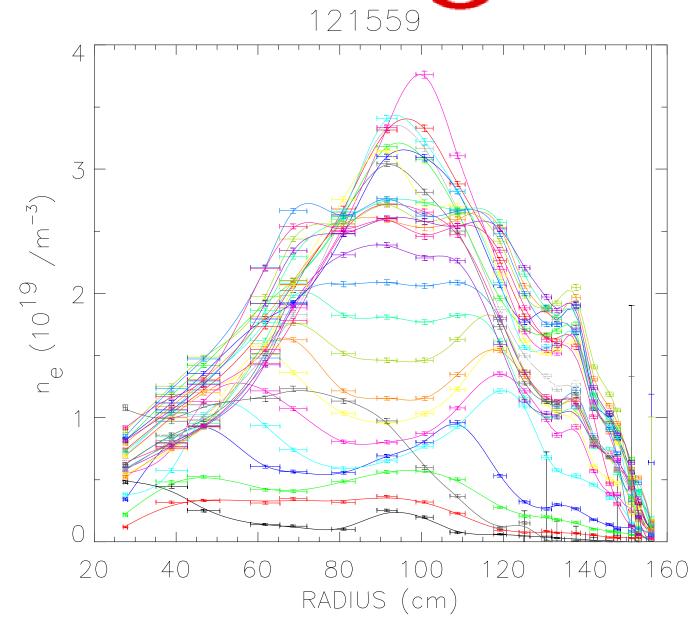


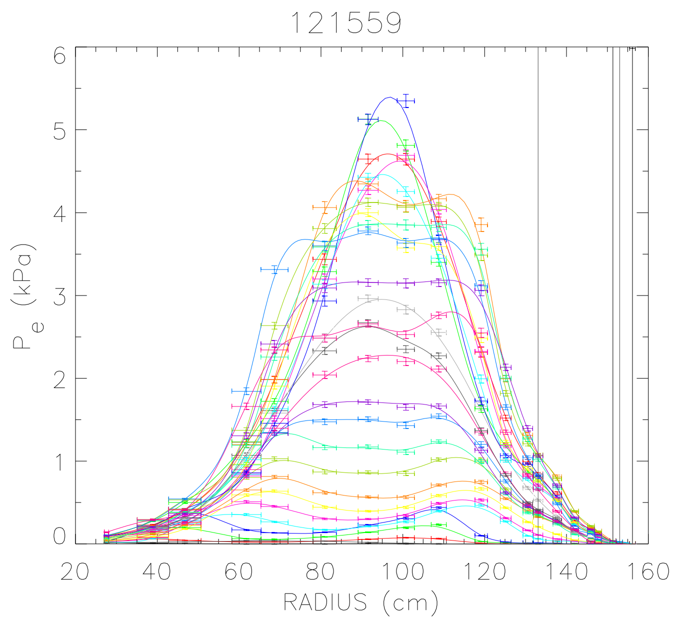


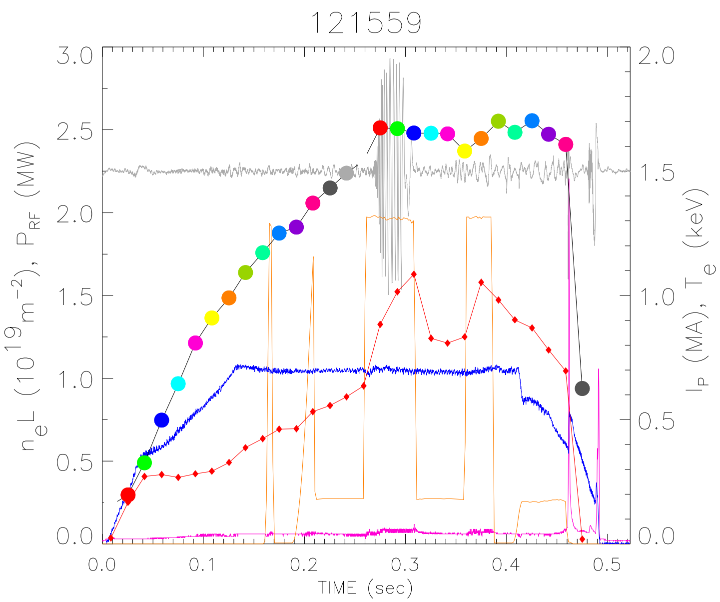


Discharge Parameters for Shot 121559 (Radial Correlation)





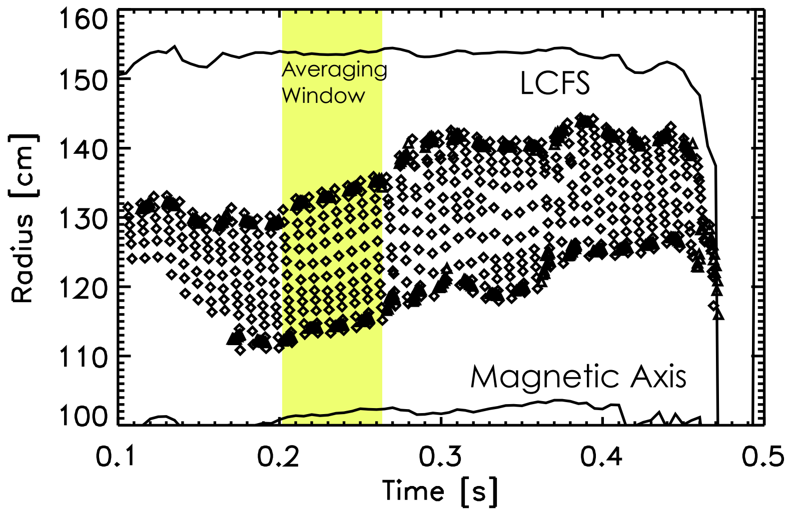




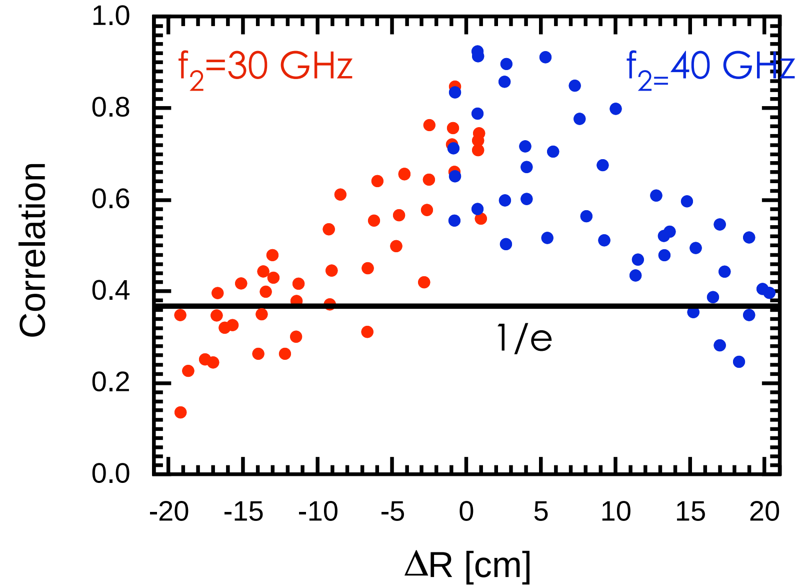
APS-DPP06, October 30-November 3, 2006, Philadelphia, PA

Radial Correlation Measurements

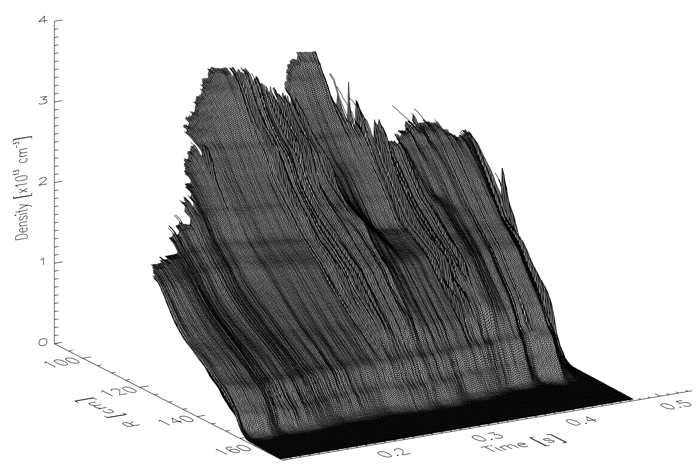
Cutoff Locations for Frequency Steps



Correlation vs Distance



Electron Density Profile Evolution

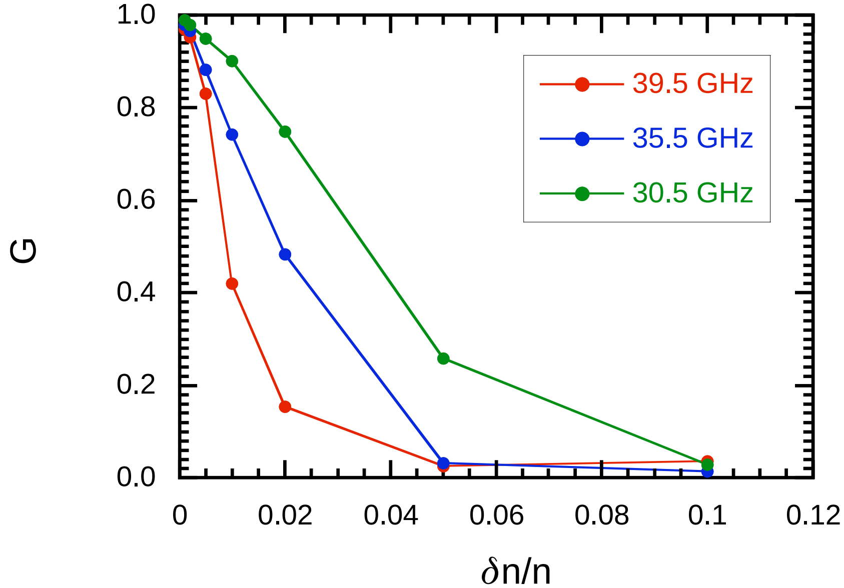


- Correlations calculated using complex amplitudes.
- Density profiles from 13-53 GHz FM-CW reflectometers.
- He discharge with RF heating.
- Spectrum of magnetics is clean.
- **Correlation function decays more slowly closer to the core.**
- **Correlation lengths are long: 15-20 cm. (Similar to homodyne measurements).**

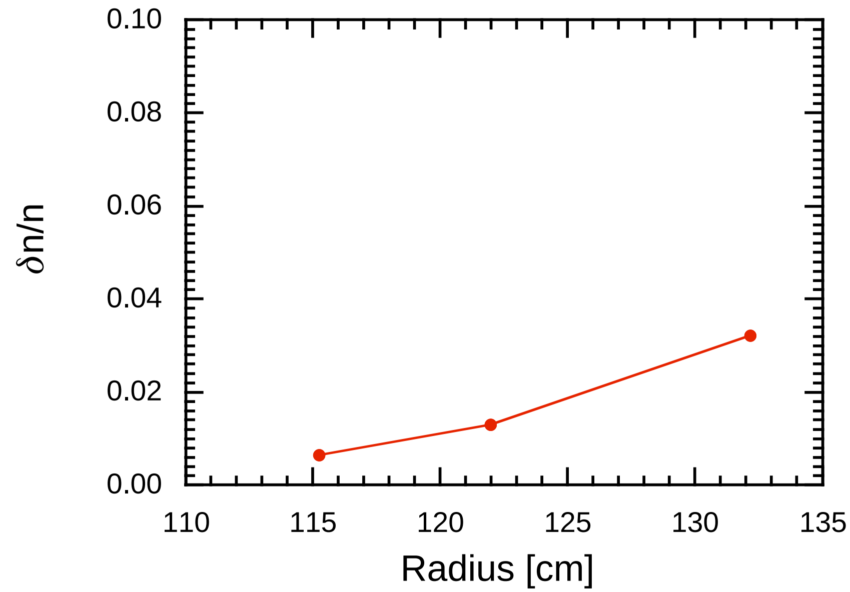
$\delta n/n$ from FWR2D and Experimental Data

NSTX

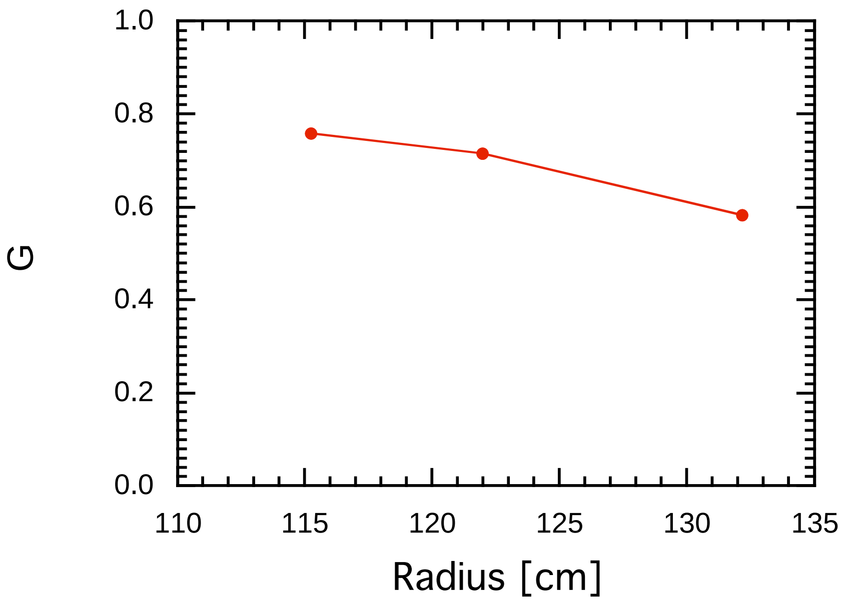
G vs dn/n from FWR2D (121559, 02-0.26 s)



G vs Cutoff Radius (121559, 02-0.26 s)



G vs Cutoff Radius (121559, 02-0.26 s)

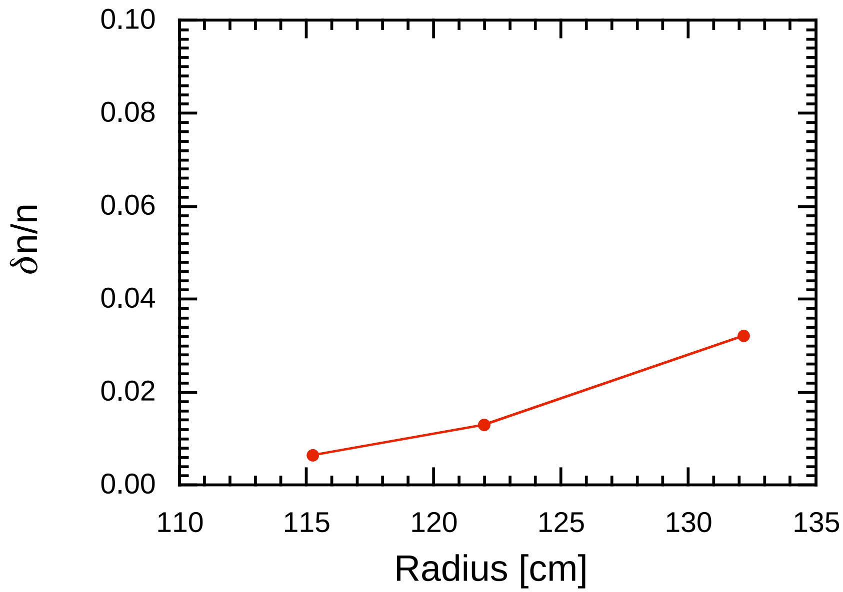


- G vs $\delta n/n$ calculated using FWR2D and profiles from shot 121559, 0.2-0.26 s. Used $(k_r)_m=(k_\theta)_m=0$ and $\Delta k_r=\Delta k_\theta=0.5\ cm^{-1}$.
- G vs radius calculated using complex ampli tude from correlation reflectometer.
- Core $\delta n/n \leq 0.6\%$ and increases with radius to several percent.
- Turbulence levels are similar to those seen in many other devices.

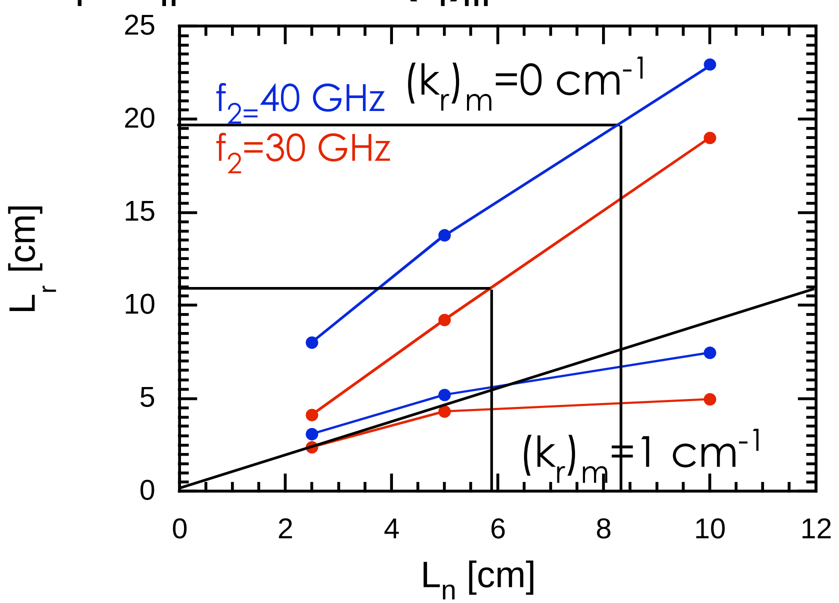
L_n Using FWR2D and $\delta n/n$ Estimate

NSTX

$\delta n/n$ Input to FWR2D



L_r vs L_n for Different $(k_r)_m$



- $\delta n/n$ radial profile from the correlation reflectometer used as input to turbulence model.
- L_r vs L_n determined for conditions similar to experiment:
  - f_2=40 GHz and f_1=28-40.4 GHz.
  - f_2=30 GHz and f_1=28-40.4 GHz.
- **Large variation of L_r vs L_n curves depending on choice of $(k_r)_m$.** Typically, maximum L_r (at smallest $\delta n/n$) approaches L_n.
- **Is $(k_r)_m$=0 the correct choice?** This correction yields L_n~8.3 cm at R~120 cm (ρ_N~0.24) and L_n~5.8 cm at R~130 cm (ρ_N~0.38), or L_n/ρ_s~15 and 10 respectively. (Closer to values seen in other devices).
- **Need a method for determining k_r spectrum.**

Summary and Future Work

- **Summary**
  - Prescription presented for using simulations with experimental measurements to characterize turbulence in NSTX.
  - The previous homodyne correlation reflectometer was upgraded for quadrature detection. The availability of the complex amplitude allows other turbulence quantities to be calculated ($\delta n/n$, k_r spectrum?) that are key parameters for the simulation input.
  - Preliminary estimates of $\delta n/n$ and L_n by comparing with 2-D full wave simulations using FWR2D code (k_r spectral shape must be assumed).

- **Future Work**
  - Poloidal correlation data also available and will be presented elsewhere.
  - Use of single sideband modulators to generate IF of several MHz for better S/N ratio.
  - Explore the possibility of radial k spectrum using $\delta\phi$ information from fast sweeps.
  - Investigate poloidal velocity shear and its connection with turbulence.
  - Knowledge of plasma flows will allow assessment of turbulence decorrelation times.
  - Comparison with results from GYRO.

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